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FATIGUE TESTS OF PLATES ~~AND~~ BEAMS WITH STUD SHEAR CONNECTORS

By
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A Report of an Investigation Conducted
by
THE CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF ILLINOIS
In Cooperation With
GREGORY INDUSTRIES, INC.

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS
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1. INTRODUCTION

1.1 General Remarks on Fatigue of Composite Beams

During the past few years there has been a great increase in the use of composite construction in both bridges and buildings. This increased use has produced some new proposals for shear connector design and, more significantly, has resulted in applications of shear connectors in a variety of structures utilizing a number of different steels. Basic research work on composite construction was carried out several years ago, but the increased interest in this structural system has caused renewed interest in a number of questions not answered in the earlier studies.

Most of the research work which had been conducted in the past has been carried out primarily for one of the two following purposes. Push-out tests(1)*, designed to determine the shear capacity of the many varieties of connectors and to study the load transfer distribution, constitute the most common investigations. The second most common type of study has been conducted to determine the static flexural strength of composite beams. Very few fatigue tests were included in the earlier work.

This situation is not surprising since in most applications of composite construction the shear connectors are attached to a steel flange which is subjected to flexural stresses which are usually compressive or, at most, very small tensile stresses. In this case the only fatigue problem is associated with the connector itself. The interest in the use of composite construction along the entire length of continuous structures and the desire to use higher strength steel in many applications has raised questions in connection with the fatigue resistance of such structures.

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* Numbers in parentheses refer to the bibliography.

In these latter applications referred to, it is necessary to provide a sufficient margin of safety to preclude fatigue failure of the flange of the beam. Shear connectors attached to the tension flange or to high strength steels where a larger stress range is possible could serve as points of initiation for progressive failure. The program reported herein was undertaken to study this problem.

1.2 Object and Scope of Investigation

As pointed out briefly in the previous paragraph the primary objective of this program was to study the effect of shear connectors on the fatigue life under circumstances where the connectors are attached to the tension flange and to study the influence of flange material on this behavior. In order to study these two problems work was undertaken on several different materials with varying chemical compositions and with different strength levels.

The program included a rather extensive series of tests on flat plate type specimens. These specimens were fabricated from two different materials. For the different types of materials studied, one or more stud shear connectors were attached in a single line transverse to the direction of stress. Another variable, intended to permit a study of the effect of stud spacing, was the width of the plate. In one series of tests the welding procedure used to apply the studs was altered.

Flat plate fatigue tests were conducted on stress cycles of complete reversal, zero-to-tension and partial tension-to-tension. A few supplementary tests were conducted to investigate the effect of geometry in the region of the connection between the plate and the stud shear connector.

The second phase of the program was carried out on nine beam specimens which were divided into three groups of three beams each. All beams were loaded in such a manner that the flange to which the stud shear connectors were attached was subjected to a tensile stress. The first group of beams was tested without any stress applied to the shear connectors. This series of beam tests could then be directly related to the flat plate tests to study the effect of stress gradient.

Bending of the beam and flexing of the stud simultaneously were studied in the other two series of beam tests. Two different methods were used to accomplish this loading condition. The studs of one group of beams were loaded by means of pre-tensioned mechanical flexors fabricated specifically for this purpose and provided with strain gages to monitor the load. In the final group of beams a reinforced concrete slab was cast so as to closely resemble the situation as it actually exists in practice.

1.3 Acknowledgments

The tests described in this report were carried out during the course of an investigation conducted in the Engineering Experiment Station of the University of Illinois. The program was carried out with funds provided by Gregory Industries, Incorporated.

The investigation constitutes a part of the structural research program of the Civil Engineering Department of which Dr. N. M. Newmark is the Head. The research was carried out by K. A. Selby, Research Assistant in Civil Engineering under the supervision of J. E Stallmeyer, Professor of Civil Engineering.

The authors wish to express their appreciation to a number of persons on the University's staff who assisted in the conduct of the investigation. These include W. T. Becker, Research Assistant, who conducted the metallurgical studies and the members of the Civil Engineering Shop who prepared the test members.

2. DESCRIPTION OF SPECIMENS AND TEST PROCEDURE

2.1 Materials

Three different steels were used in the fabrication of the flat plate specimens and the beam specimens reported herein. These three steels will be referred to in the following discussion by their ASTM designations.

A7F Steel: During the initial phases of the study reported, one series of eight plate specimens (GIA Series) was fabricated from a steel which was available in the laboratory and which had been purchased some time earlier to conform to ASTM A7-58T. Coupon tests carried out in the laboratory indicated that this steel failed to meet the tensile requirements of this specification. In future discussion this steel will be referred to as A7F.

A441 Steel: All of the remaining flat plate tests were carried out on specimens fabricated from a steel which satisfied the requirements of ASTM A441-60T. This material was also used as the flange material in the beam tests which are reported later.

A373 Steel: The third type of steel used in this investigation served for the web material of the nine beam specimens. This steel met the requirements of ASTM A373-58T. Due to the location of this material in the beam specimens and the type of tests being conducted this steel did not affect the fatigue life being studied.

The chemical composition of all of the base materials and the physical properties of these same base materials are presented in Tables 1 and 2.

2.2 Description of Test Specimens

All specimens were fabricated in the Civil Engineering Shop at the University of Illinois. After fabrication, they were shipped to Gregory Industries, Incorporated in Lorain, Ohio, manufacturers of Nelson Stud Welding Equipment, where the studs were affixed.

The entire test program was broken down into five different series of tests, designated GIA through GIE. Each specimen has received a designation consisting of three letters to indicate the specific series followed by a number to distinguish the particular test specimen within that series (e.g., GIB12).

2.2.1 Plate Specimens. The dimensions of the various plate specimens are shown in Figs. 1, 2 and 3. The details of the welding procedure used in the application of the studs to the individual specimens are listed in Table 3.

GIA Series: This series consisted of eight plate specimens machined from A7F steel. Each specimen was machined to the dimensions shown in Fig. 1(a) before the stud was attached. Each specimen was provided with a single stud on a 3 1/2 in. by 1/2 in. cross-section. Throughout all five series of tests the material thickness was maintained constant at 1/2 in. in order to reduce the number of variables involved.

GIB Series: Basically the GIB series, which involved twenty specimens, was identical in all respects to the GIA series except that A441 steel was used instead of A7F. Specimens GIB16 through GIB20 were subjected to a slightly different welding procedure and several specimens had slight variations in geometry as will be outlined in Section 2.3.

GIC Series: The only significant difference between the five GIC specimens and those of the GIB series was the width of the cross-section. In this series of tests the width was increased to 5 in. Both series were fabricated from A441 steel and contained a single stud attached at the center of the flat plate specimen.

GID Series: In order to study the effect of multiple studs ten flat plate specimens were machined to a 10 in. width across the test section. These specimens were then provided with either one, three, or five studs attached in a single line transverse to the direction of applied stress. In addition to the increased width these specimens, as well as Series GIC, were 4 ft. long while specimens of Series GIA and GIB were only 2 ft., 8 in. long. The difference in length was necessitated by the increased cross-sectional area which required loadings of such a magnitude that they could only be produced by the larger testing machines.

The cross-sections of all flat plate specimens through the line of studs are presented in Fig. 4.

2.2.2 Beam Specimens. The nine steel beams used in this phase of the investigation were fabricated from three flat plates. The beams had an over-all depth of 12 in., a flange thickness of 1/2 in. and a web thickness of 3/16 in. Each of the beams was then provided with two rows of studs spaced 2 1/2 in. apart. Each of the rows contained nine studs at a spacing of 10 in. along the length of the beam. These nine specimens were then subdivided into three groups of three specimens each and subjected to different loading conditions.

Specimens GIE1 through GIE3 were tested as simple flexural members with no external loads applied to the stud shear connectors. Specimens GIE4 through GIE6 were altered in such a manner as to remove the heads from the eight centrally located studs. Specially prepared and calibrated connectors were placed over four pairs of studs as shown in Fig. 5(b). These connectors were made so that they could be pre-tensioned to produce any desired shear force in the studs. The force in the connector was measured by strain gages attached to the connector and calibrated in a static testing machine. Additional strain gages were attached to the beam specimens in the case of specimens GIE4 and GIE5 in order to determine the strain distribution across two different cross-sections. The output from these strain gages was recorded during the period of the fatigue test on a Sanborn recorder.

In the case of specimens GIE7 through GIE9 the studs were incased in a reinforced concrete slab as shown in Fig. 5(c). A mixture of graphite and linseed oil (one part graphite to 4.4 parts of linseed oil) was placed on the steel surface in order to destroy the steel-concrete bond. In this way all of the shear force must be transmitted through the studs. The reinforcing steel consisted of three No. 6 bars which were located 3/4 in. below the lower flange of the steel beam. Beams GIE7 and GIE9 were instrumented with strain gages at various locations and through the depth of the steel beam in order to determine the strain distribution through the depth and the extent to which this strain distribution was altered as a result of the shear force transmitted through the shear connector.

2.3 Object of the Individual Test Series

GIA Series: The purpose of this series of tests was to obtain a basic S-N curve for A7F steel on a zero-to-tension stress cycle so that these results could be compared with similar tests on A441 steel.

GIB Series: In this series S-N curves were to be established for both zero-to-tension stress cycles and a fully reversed stress cycle. On the basis of the results obtained on those two series of tests an estimate was made of the stress cycle which would produce failure at 2,000,000 cycles on a one-half tension-to-tension stress cycle.

Specimens GIB16 through GIB20 were produced with a slightly different stud welding procedure from the rest of the specimens in this series. The purpose of these specimens was to investigate the effect of altering the stud welding procedure on the fatigue life and the fatigue behavior of this material. Two specimens, GIB11 and GIB12, were subjected to additional treatment after the studs had been attached. This treatment consisted of grinding the upset in such a manner that it produced a smooth transition from the plate to the stud. These tests were carried out in order to evaluate the significance of the geometry of the upset.

In two other specimens, GIB19 and GIB20, the studs were completely removed by grinding. The grinding was carried out so as to approximate the surface condition of the surrounding plate as nearly as possible. In these cases the notch effect of the upset and the presence of the stud had been completely removed, so that any difference in the results from plain plate test results would indicate the effect of welding on the base material.

The tensile strength of Series GIA and Series GIB specimens was checked by means of three static tests. These tests provided a basis for comparison of the various fatigue strengths with the static ultimate strength of similar specimens.

GIC Series: The function of this series was to determine the fatigue strength for failure at 2,000,000 cycles on a one-half tension-to-tension stress cycle. Specimens in this series were 5 in. wide so that a comparison with the results of the GIB series would give some indication of the size effect. Specimen GIC5 was not subjected to any fatigue loading but was examined metallurgically to determine the hardness distribution near the stud.

GID Series: All of the GID series specimens were tested under a one-half tension-to-tension stress cycle. Specimens in this series were provided with either one, three, or five studs on a single line transverse to the direction of applied stress. In all cases the fatigue strength for failure at 2,000,000 cycles was desired. The single stud specimens, GID1 through GID3, would provide data for a further evaluation of the effect of width since the cross-section was 10 in. wide in this series. Comparison of the three groups of specimens within this series provides an evaluation of stud spacing.

GIE Series: This series was divided into three groups of three beams each. In every case the fatigue strength for 2,000,000 cycles under a one-half tension-to-tension stress cycle was desired. The purpose of the first group of tests, GIE1 through GIE3, was to compare the fatigue strength of the flange with the attached studs with the results of the axially loaded plate specimens.

The other two groups were intended to show the effect of transmission of shear force through the stud connector at the same time the beam is being subjected to primary bending. This, of course, is the loading condition which occurs in actual composite construction. Some strain gages were attached to several of these specimens in order to check the strain distribution across several cross-sections.

2.4 Testing Equipment and Procedures

All of the fatigue tests were conducted in University of Illinois lever type fatigue machines. Series GIA and GIB, the small plate specimens, were tested in machines with a total load capacity of 50,000 lb. while all of the other tests were conducted in the larger 200,000 lb. machines. These machines, while similar in their basic operation, varied in speed from 300 to 100 cycles per minute.

Schematic diagrams of the University of Illinois fatigue testing machine adapted for axial and flexural loading can be seen, respectively, in Figs. 6 and 7. By adjusting the variable throw eccentric and the turnbuckle, which is immediately above it, the required stress cycle can be applied to the specimen. The load is determined by means of an Ames dial which measures the deformation of the dynamometer.

A micro switch near the specimen end of the machine is adjusted so that excessive deflection of the specimen trips the switch and stops the machine. During the progress of the fatigue fracture the load is adjusted so that the specimen is subjected to a relatively constant value of load. Failure is defined as having occurred when the specimen could no longer withstand the prescribed load without yielding.

Prior to testing, the plate specimens were measured to determine the average cross-sectional area at the position of the stud. This area was then used to determine the load so that the desired average stress would exist at the expected failure location.

In the case of the beam specimens, the loads and, therefore, the moments which were acting on the beam were calculated by means of the deformation of the dynamometer. The stresses were obtained by means of the simple flexural formula using the moment of inertia computed for the fracture section.

3. TEST RESULTS AND DISCUSSION

3.1 Presentation of Test Results

The results of individual tests carried out on the plate specimens are presented in tabular form in Tables 4, 5, 6, 7, 8 and 9. These same results are presented in the form of S-N diagrams in Figs. 8, 9, 10, 11 and 12. A brief study of the data presented will indicate that there was a minimum amount of scatter and good consistency among the results.

The individual test results for the beam specimens are presented in Table 12. In this table the designation under type indicates the condition of the beam during the progress of the test.

The individual test series are discussed and compared in the paragraphs which follow.

3.2 Fatigue Test Results for Plate Specimens

The fatigue results showed amazingly little scatter so that relatively few tests gave a strong indication of the fatigue resistance of plate specimens with attached studs. Most of the tests carried out were intended to determine the magnitude of the stress cycle which would result in failure at 2,000,000 cycles. A study of the various S-N diagrams indicates that such stress cycles are as follows: for complete reversal a stress cycle from 8.0 ksi compression to 8.0 ksi tension (a range of 16.0 ksi), for the zero-to-tension stress cycle from 0 to 16.0 ksi (a range of 16.0 ksi), and for a stress cycle ranging from one-half tension-to-tension from +14.0 ksi to +28.0 ksi (a range of 14.0 ksi). It should be noted that the stress range remains almost constant as the stress cycle changes.

3.2.1 Influence of Base Material on the Fatigue Life. An indication of the effect of variations in base material is obtained by comparing the results of the GIA and GIB specimens. Figures 8 and 9 present the results for specimens which are similar in all respects except for base material. Seven GIA specimens, fabricated from A7F steel, and six GIB specimens, fabricated from A441 steel, were subjected to a zero-to-tension stress cycle. For each group of tests the results formed a very narrow scatter band, as indicated on the figures. When the data are superimposed the two scatter bands coincide almost perfectly, as is seen in Fig. 10.

It must be noted that this excellent correlation involved only a few tests of two steels for one particular type of stress cycle. These results are similar to results which have been previously obtained on these materials in studies of the effect of butt-welded joints.

3.2.2 Effect of Stud Welding Procedure. In order to study the effect of variations in the stud welding procedure, five specimens of the GIB series were fabricated with a substantially different welding procedure as compared to that used for the preparation of the remainder of these specimens. For specimens GIB16 through GIB20 the weld current was 1,450 amperes, the arc voltage was 33 volts, and the weld time was 76 cycles. The remainder of the series, specimens GIB1 through GIB15, were prepared with a weld current of 1,500 amperes and an arc voltage of 33 volts for 58 cycles. This means simply that specimens GIB15 through GIB20 were subjected to twenty-six percent more heat than other specimens of this type.

Two of these specimens, GIB16 and GIB17, were subjected to a zero-to-tension stress cycle in the as-produced condition. The results of these tests are presented in Fig. 9 and no significant difference in fatigue life was obtained. One specimen, GIB18, was subjected to a one-half tension-to-tension stress cycle in the as-welded condition and a study of the results given in Table 7 indicates that no significant difference could be observed. The remaining two specimens with the modified welding procedure, GIB19 and GIB20, were subjected to special tests which are reported in a later paragraph.

On the basis of the tests conducted it can be concluded, within the limits of the variations in welding procedure studied, such variations had no significant effect on the fatigue life.

3.2.3 Effect of Upset Geometry. In order to study the effect of geometry in the region of the upset, four specimens of the GIB series were subjected to treatments which altered the geometry in this vicinity. Two specimens, GIB11 and GIB12, were ground in such a manner that their upsets formed a smooth transition from the plate surface to the stud. Each of these specimens was tested at a different zero-to-tension stress cycle for which results were available for specimens with the as-produced geometry. The results of these tests are presented in Table 5 and are reported in Fig. 12. An examination of Fig. 12 indicates that in both cases the fatigue life of specimens so treated was approximately double that of the as-produced specimens.

For two other specimens of this series, GIB19 and GIB20, the studs were completely removed and the surface smoothness was ground to approximate that of the surrounding plate. This alteration should remove completely the geometrical effect and, therefore, any difference in fatigue life between these specimens and the fatigue results for plain plate specimens could be attributed to the effect of welding on the base metal. The results of the tests conducted on these two specimens are reported in Table 5. They proved to be significantly more fatigue resistant than all other types of specimens in this program. A comparison of these test results with test results obtained in previous investigations of plain plate material of A441 steel indicates that these results are not quite as good as the results obtained for plain plate specimens. Therefore, one can conclude that even when the stud is completely removed from the plate to which it is attached, some effect of the welding remains and the fatigue resistance is just slightly less than what would have been obtained for plain plate material.

3.2.4 Significance of Stud Spacing. The effect of stud spacing can be studied by comparing several different series of tests. In one case, one can consider the effect of plate width for the various specimens which were provided with a single stud. Series GIB, GIC, and GID all contain test results for single stud specimens subjected to a one-half tension-to-tension stress cycle. The results of these tests are tabulated in the individual tables and have been presented for purposes of comparison in Fig. 13. These results indicate that a slight increase in fatigue life is obtained when the width of the plate is increased.

These results indicate that, although the plate to which the stud is attached is continuous, the stud acts somewhat like a hole in a flat plate specimen. In this case, the stress concentration effect increases as the width of the plate decreases. This result is directly in line with what one would expect for a plate with a hole.

The effect of stud spacing can be studied by examining the results of the GID series which are presented in Table 9 and which are shown graphically in Fig. 14. All tests in this series were conducted on a stress cycle which varied from one-half tension-to-tension. The specimens in this series were all 10 in. wide and were provided with one, three, or five studs. In the multi-studded specimens it might easily be reasoned that since the plate is heated and cooled more slowly when several studs are attached in succession, the plate should contain residual stresses of a lower magnitude and that the studs should represent less of a stress concentration. On the other hand, one could easily argue in favor of a reduced fatigue life because of the increased number of stress concentrations where fatigue fracture could initiate.

An examination of the test results indicate that neither of these factors is very dominant. As seen in Fig. 14, the single studded specimens are slightly more resistant to fatigue failure. However, a study of the results presented previously in Fig. 13 and those presented in Fig. 14 reveal that the results for a single stud attached to a 3 1/2 in. wide plate, corresponding to a stud spacing of 3 1/2 in., and the results for the single stud attached to a 5 in. wide plate, corresponding to a stud spacing of 5 in., give results which are in line with those presented in Fig. 14. Although the results indicate that there is a slight decrease in fatigue life as the number of studs in any one line is increased, this difference is not significant when converted to stress levels which would produce failure at the same number of cycles.

It is interesting to note at this time that the specimens with more than one stud attached always had more than one independent failure surface. These failure surfaces occurred independently and almost simultaneously. In a number of cases failures occurred above and below the same stud. These fractures indicate that failure is not brought on by one particular weak spot, but that the effect of the studs is extremely consistent and that failures initiate at a number of independent locations and propagate individually.

3.2.5 Comparison with Other Test Results. Table 10 presents a tabulation of test results obtained in this and previous investigations[2,3] with similar materials. Previous tests have been conducted on plain plate material of A441 and A7, double-Vee butt-welded joints in A441 steel and plate material with a single hole. This tabulation of results indicates that the attachment of studs is somewhat more severe than the presence of a hole or the presence of a double-Vee butt-weld. On the basis of the results for plain plate specimens of A441, the plate with studs has an effective stress concentration factor in fatigue of approximately 2.5.

3.2.6 Static Tests. During the course of the investigation several static tests on plain plate specimens with a single attached stud were subjected to static loading. The results of these tests are presented in Table 11 and indicate that the presence of the stud did not in any way influence either the yield point or the ultimate strength of the base material. A comparison of these test results with those presented earlier in Table 2 indicates that the average of the yield point obtained is at least as high as that obtained on the coupon tests and that the ultimate strength is somewhat higher. In the case of the A441 specimen, no yield point was recorded but the ultimate strength is very close to that obtained on the coupon tests and is well in excess of that required by the specifications.

3.3 Fatigue Results of Beam Specimens

The purpose of this series of tests was to provide a correlation between the results of the flat plate specimens and the stress conditions as they actually occur in composite construction. In addition, as previously noted, this series of specimens was divided into three groups, one group being subjected to flexural loading without any load being transmitted through the stud shear connector, one series subjected to flexural loading with a shear loading applied by means of special mechanical adapters and a final series of tests in which the stud was imbedded in a concrete slab and subjected to shear force transmitted by virtue of the composite action obtained.

All of the tests on beam specimens were conducted on a stress cycle which ranged from approximately one-half tension-to-tension with the stress range chosen so as to produce failure in approximately 2,000,000 cycles. The results of all of the tests conducted on beam specimens are presented in Table 12.

3.3.1 Plain Beam Tests. The results of the plain beam tests, specimens GIE1 through GIE3, indicate that a stress cycle alternating between 16.4 ksi tension to 32.8 ksi tension is required to produce failure in approximately 2,000,000 cycles. This stress range is slightly higher than the stress range which produced failure at this same life in the plain plate specimens. Although no direct comparison can be made since the flange used in the beam tests was provided with two studs on a 6 in. wide plate and a spacing between studs of 2 1/2 in., the results can be compared with specimens of the GIC series and the GID series. In the case of the GIC series a single stud was attached to a 5 in. wide plate. In the GID series specimens are included which provide a stud spacing of 3 1/4 in. and a stud spacing of 2 in.

In all of the cases referred to, a stress cycle ranging from 14.0 ksi to 28.0 ksi produced failure in approximately 2,000,000 cycles. This slight increase in stress cycle to produce failure in 2,000,000 cycles in the beam specimens is in all probability attributable to the stress gradient which exists through the flange and the relief which is provided for the stress concentration effect of the stud. Even if one compares the average stress across the total flange area the stress range for the beams in the current series of tests was from 15.7 ksi to 31.4 ksi.

These results are extremely encouraging in view of the fact that they indicate that tests carried out on plain plate specimens give an excellent indication of the strength which can be expected of similar installations on beams.

3.3.2 Beams with Stud Flexors. Specimens in this series of tests were identical in all respects to those in the previous group except that a shear force was applied to several of the stud shear connectors by means of a mechanical attachment. As mentioned earlier the heads of several studs in the vicinity of the center of the beam were removed so that mechanical flexors could be attached. Load in the flexors was adjusted by means of strain gages. A photograph of the flexor used for this purpose and a view of one beam with flexors in place are shown in Fig. 15. The load applied by this means was located approximately 3/4 in. from the surface of the flange.

At the beginning of the fatigue test the load in the flexor was adjusted so that at maximum flexural load the shear stress in the studs to which the flexor was attached had a nominal value of 15,000 psi. All beams were tested on a stress cycle which varied from one-half tension-to-tension. The load in the flexor, on the other hand, remained nearly constant at the magnitude applied at the beginning of the test. It was possible to monitor the load in the flexor during the individual test cycles and also at various stages during the progress of the test.

Such monitoring indicated that at no time during the course of a test on any specimen did the load in the flexor drop below a value of 80 percent of the maximum value set. In only a few cases did the load on the flexor drop to this value. In the other cases the load in the flexor did not drop below a value of 85 percent of the maximum value. This fact is particularly significant since the stress levels reported in Table 12 are computed on the basis of the section properties of the base beam at the location of the failure. No account has been taken of the effect of the stud flexor on the distribution of stress through the depth of the beam. The local effect of the load transmitted through the stud has also been neglected in the stresses reported.

All failures in this series of beam specimens occurred on the side of the stud away from the flexor used to apply load to the stud. Two failures occurred at the center-line of the beam where the moment and corresponding flexural stress have the maximum value. The other failure occurred at a stud at a distance of 10 in. from the center-line of the beam. At this point the moment and flexural stress have a value equal to 91 percent of the maximum value at mid-span. Since these values are based on nominal stress calculations and neglect the local effect of the load in the stud, one must conclude that the actual difference in stresses for these two fracture locations is even smaller than that indicated by simple flexural calculations.

The foregoing discussion serves to explain why the stresses reported in Table 12 for this particular series appear to be somewhat low. With the load transmitted through the stud, however, these beams still required a stress range of about 12.5 ksi on a one-half tension-to-tension stress cycle to produce failure in 2,000,000 cycles.

3.3.3 Beams with Reinforced Concrete Cover. All beams in this series were provided with a reinforced concrete cover. The amount of reinforcement placed in the concrete was calculated to produce in the studs a maximum shear force equal in magnitude to the maximum load which was applied in the previous series by the mechanical flexors. The reinforcement was placed in one layer near the tension flange. This location of the reinforcement resulted in the proper magnitude of shear force in the studs and a distribution of flexural stresses in the base beam to ensure failure under the applied loads in approximately 2,000,000 cycles.

Specimens in this series, as in the previous series, were provided with strain gages at several locations along the length of the beam. The strain gages were distributed through the depth of the beam in order to indicate the extent to which the concrete and the reinforcement in the concrete acted as a composite section. These gages were located at cross-sections which corresponded to the location of studs and at the section mid-way between the studs.

Upon application of load during the progress of the fatigue test, cracks appeared at each row of studs. These cracks at the stud locations were the only visible concrete cracks which formed during the course of the fatigue tests. The presence of the cracks caused fluctuations in the location of the neutral axis as determined from the strain gages.

In the region between studs where the concrete was not cracked, the neutral axis is shifted toward the flange to which the shear connectors are attached. At the stud locations where the concrete was cracked, the neutral axis shifted slightly away from the tension flange of the beam. Near the ends of the span, between the rows of studs, the neutral axis shifted to a location which indicated that the concrete in this region is almost completely effective.

For beams in this series it is possible to compute the nominal stress on the extreme fiber of the tension flange in several different ways depending on the basis used for these calculations. One can assume that only the steel beam resists the bending moment, in which case the stress cycle for beams GIE7, GIE8 and GIE9 in the fatigue test was from +21,800 psi to +43,800 psi for a total range of 21,800 psi.

The stress cycles reported in Table 12 were calculated on the basis of a cracked section for all of the concrete slab. On the basis of the results of the strain gage studies this is the most reasonable assumption for the actual state of stress. A very reasonable check on these stresses was obtained by means of the strain gages. These gages indicated a linear strain distribution throughout the web of the beam. In both flanges the strain recorded by the gages was less than the value which would be expected if the web strains are extrapolated. This non-linearity is caused by local effects on both flanges. In one flange the indicated strains are affected by the presence of the loading heads used in the fatigue machine. On the other flange the strains are very strongly affected by the proximity of the gages to a section where the concrete is cracked and also by the local effects of the load transmitted by the stud shear connector.

If the linear strain distribution recorded in the web is extrapolated to the flanges the moment determined from this distribution is in almost complete agreement with the moment determined on the basis of statics for the beam structure. This would certainly seem to verify the fact that deviations from this distribution, as recorded by the strain gages, are caused by the local circumstances noted previously.

All of the beams in this series failed by propagation of a fatigue crack through the tension flange. These cracks initiated on the edge of the stud shear connectors, as in the case of all previous tests conducted on beams and on plate specimens. The fractures initiated at the row of studs just removed from the pure moment region of the beam span. This location agrees with what would be expected since between the support point and the point of load application the beam is subjected to a constant value of shear and a linear increase in bending moment. All studs in this region, therefore, are required to transmit the same shear force and the one row of studs nearest the point of maximum moment is the most likely point for any fatigue failure to initiate. While the row of studs at mid-span is subjected to a slightly higher moment they are not subjected to any shear force and are therefore not the most critical.

On the basis of all of the beam tests conducted it would appear that the fatigue resistance of beams with reinforced concrete cover is the same as that obtained from the plate tests. A comparison of the beam tests indicates that the presence of the reinforced concrete produces a condition which is slightly more severe than the plain beam but not quite as severe as the case where the studs are loaded by the mechanical flexors.

3.4 Fracture Surfaces

The fracture surfaces obtained in all of the fatigue tests followed the same pattern with the fracture initiating at or near the edge of the stud which is first encountered by the axial stress flow. Initial cracks occurred at either one of these locations or at both of them, more or less simultaneously. As the test progressed one of the cracks, in those cases where two cracks initiated, propagated more rapidly and caused the other crack to stop propagating.

Typical fracture surfaces for the various specimens tested are contained in Figs. 16 through 19. Figure 16(a) shows the fracture surface of two specimens fabricated from A7F steel while Fig. 16(b) shows the fracture surface of two specimens fabricated from A441 steel. The general features of the fractures are very similar and indicate the general nature of all of the fracture surfaces encountered in the test program. Typical features of the fracture surface include a region generally referred to as the "thumb-nail," where the rate of propagation is relatively slow. As the crack grows in size the rate of propagation increases and the fracture surface is somewhat rougher. The final stage of fracture is a static failure of the remaining area of the test specimen.

Particular note should be taken of Fig. 16(b) which shows the fracture surface for GIB1. In this specimen the fracture actually initiated under the upset. As the crack propagated it cut across the upset as well as the parent plate, so that when final fracture occurred a portion of the upset was torn from around the stud. This type of failure was encountered in a few of the cases in this study and was primarily affected by the extent to which the upset was bonded to the parent plate. In those cases where the upset was not completely bonded, the critical location was actually under the upset and the fracture propagated from this point.

Figure 17 shows the fracture surfaces which resulted in those cases where the geometry of the upset was altered. The top portion of this figure shows the result for the case in which the upset was ground to a smooth transition between the parent plate and the stud. Failure surfaces in this case are very similar to those previously presented except that the region of slow propagation is somewhat larger than in the case where the upset is subjected to no treatment. Part (b) of this figure shows the fracture surfaces which resulted in the two cases where the stud was completely removed. Here again the fracture surface is not greatly different from that previously reported, except that the region of slow propagation is somewhat larger. It is interesting to note that in this case the failures initiated at locations which corresponded to where the edge of the stud would have been, had it not been removed. This would indicate that the metallurgical structure in this area is weaker as a result of the changes which occur during the welding process. A check of the fatigue test results will indicate, however, that the influence of this metallurgical change is not nearly so great as the geometrical effect of the presence of the upset.

Figure 18 shows the fracture locations for the cases where a single stud was attached to a wider plate. The fracture surfaces in these cases were similar to those previously presented. A very interesting feature of the multiple stud specimens is shown in Fig. 19, where typical failures of wide plates with multiple studs are presented. Close examination of the photograph of specimen GID6 reveals several independent cracks which have initiated in a manner identical to that obtained for the plate specimens with a single stud. The photograph of specimen GID8 shows how these cracks which initiate and propagate independently join up to form a continuous crack which eventually causes final fracture.

Although it is not readily apparent in the photographs of the specimens with multiple studs, close examination of the specimens revealed that a large number of independent cracks had actually initiated. In the case of the specimens with three studs at least three independent cracks were initiated. In the case of the specimens with five studs the number of independent cracks varied from six to eight, which indicates that in all cases at least some cracks were initiated on both sides of the studs. This observation is of particular import since it indicates that the fatigue resistance of such installations is not a case of the weakest link but rather that the fatigue resistance of all of the studs is virtually the same and that fracture initiates at all studs at very nearly the same number of cycles. Some further indication of this fact is contained in the following section dealing with metallurgical examinations.

4. METALLURGICAL STUDIES

4.1 General

As a part of the program it was essential that detailed metallurgical studies be carried out to determine the nature of the microstructure as influenced by base material, heat input and amount of material available to absorb the heat input during the welding process. A total of five different specimens were subjected to detailed examination. Most of these specimens were examined after completion of the fatigue test. In one case the specimen was subjected to metallurgical study in the as-produced condition in order to verify that at the examination section the fatigue loading had produced no change.

Both macrographs and micrographs of areas of interest were taken for all specimens studied. The studies also included detailed hardness traverses from base plate material to unaffected base stud material, across the heat-affected zones and the weld metal microstructure. Details of the findings of these studies are included in the following sections.

4.2 Microstructures

The general microstructural features of the stud welds are typical of welds in general: a columnar weld metal zone, with ferrite outlining of the prior austenite matrix. This weld metal zone is a mixture of tempered martensite, ferrite and pearlite at room temperature. The next portion of the microstructure is the heat-affected zone which possesses an austenite grain size gradient (largest grains near the fusion line) which results in the presence of martensite near the fusion line. Away from the fusion line the amount of martensite decreases while the amount of pearlite and ferrite increases. Adjacent to this region is the unaffected base metal zone which consists of Widmanstätten ferrite and pearlite in a banded structure due to the hot rolling process.

Detailed macrographs and micrographs of a variety of specimens are contained in Figs. 20 through 24. Hardness surveys from the base plate material across the heat-affected zone and weld metal to the base material of the stud are contained in Figs. 25 through 28. The specific microstructures vary somewhat in width of the heat-affected zone and weld metal zones. The relative amount of martensite in the heat-affected and weld metal zones, and the fineness of the columnar structure of the weld metal, vary as a result of the difference in the heat input to the various specimens. The amount of weld metal increases with the amount of heat input to the specimens, as does the width of the heat-affected zone. Consequently, GIA2 and GIC5 have the narrowest weld metal and heat-affected zones, followed by GIB1 and GIB16, and the fineness of the weld metal structure decreases in the same order. Specimen GIB16 has a higher percentage of martensite in the heat-affected zone than GIB1.

Although an increase in heat input generally decreases the hardenability, the opposite is true for this material. The presence of the strong carbide former, vanadium, ties up some carbon and long solution times are required to take the carbon back into solution. As a result, more carbon is in solution in GIB16 than in GIB1, which accounts for the increased amount of martensite. Specimen GIB1 would be expected to have a smaller amount of martensite than GIC5 due to the lower heat input, and GIA2 would have less martensite due to the decreased hardenability of A7F steel as compared to A441 steel. Since the weld metal is formed by melting the base metal, the same trends observed in the heat-affected zone should be observed in the weld metal zones.

4.3 Hardness Surveys

As would be expected on the basis of metallographic observation, the hardness of the material increases as the percent of martensite increases. As a result the hardness of the heat-affected zone of the plate of GIB16 is considerably higher than that of GIB1, and the same is true of the weld metal zones. It is also true that the hardness of the heat-affected zone of the plate and the weld metal zone of GIB1 is considerably higher than the corresponding hardness in these regions of GIA2, due to the increased alloy content of A441 steel as compared to A7F. Table 13 contains a summary, from four different specimens, of the size and average hardness of the various zones which result from the welding operation.

4.4 Mode of Failure

Typical failure of all specimens is evidenced in GIA2. Both of the macrographs in Fig. 20 show a fatigue crack on the right hand edge of the stud which initiated at the fusion line and traversed the heat-affected zone. This crack is not the crack which resulted in final failure of the specimen but is rather 180 degrees away from the source of ultimate failure. Propagation of the crack is transgranular as seen in GIA2.

5. CONCLUSIONS

The tests reported give a very good indication of the effect of base material, number of stud connectors, spacing of stud connectors and welding procedure on the fatigue resistance. On the basis of the flat plate test series the following conclusions have been drawn.

1. In all cases the fracture initiated at the edge of the upset and propagated radially through the thickness of the plate. Almost without exception the multi-studded specimens featured more than one independent fracture surface. All multiple fractures occurred almost simultaneously.

2. The stress range to produce failure in 2,000,000 cycles varied from 16,000 psi in complete reversal to 14,000 psi in a half tension-to-tension stress cycle.

3. There was no noticeable difference in fatigue life between specimens fabricated from A7F or A441 base material.

4. Altering the stud welding procedure to supply more heat to the weld had no effect on the fatigue life.

5. Changing the stud geometry by grinding the upset to a smooth transition doubled the fatigue life. Complete removal of the studs provided an even greater resistance to fatigue loading. With the stud removed, however, the fatigue life was not as great as has been reported earlier for plain plate specimens of similar material.

6. The number of studs in a line transverse to the direction of stress and the spacing of the studs has some effect on the fatigue resistance but the effect is not very large.

The behavior of the beam specimens in all three series was very similar to what was obtained for the flat plate specimens. Excellent correlation is obtained between the flat plate specimens and the beam specimens, not only in over-all behavior but also in terms of stress levels required to produce failure in 2,000,000 cycles. The following observations have been made on the basis of the beam tests.

1. Fractures in the beam specimens were similar to those obtained in the flat plate specimens. In flat plate specimens the fracture might occur on either side of the stud whereas, in the beam specimens, the fractures occurred on the side of the stud where secondary tensile stresses, due to the loading of the stud, were added to the primary tensile flexural stresses.

2. Cracking occurred in the concrete at every row of studs and only at the studs. Although the slab used in these tests was narrow there is reason to believe that shear connectors in the negative moment regions might prove to be an effective means of crack control.

3. The half tension-to-tension stress cycle to produce failure in 2,000,000 cycles for the various groups of beams tested was:

Plain Beams	:	16.4 ksi to 32.8 ksi
Beams with Flexors	:	12.5 ksi to 25.0 ksi
Beams with Concrete	:	14.0 ksi to 28.0 ksi

In view of the extent of the argument between the results of the flat plate specimens and the beam specimens it would certainly appear that the flat plate tests give a satisfactory indication of the behavior of similar beam tests.

With this as a basis the Modified Goodman Diagram presented in Fig. 29 should serve as a basis for the development of suitable provisions for fatigue in the case of designs which utilize stud shear connectors for composite action in negative moment regions. This diagram yields a stress range of 16,000 psi for complete reversal, 16,000 psi for zero-to-tension and 14,000 psi for half tension-to-tension for failure in 2,000,000 cycles. A somewhat smaller range would be required for stress cycles above this level. Applying a factor of safety of approximately 1.6 on these stresses results in permissible stress cycles of approximately 10,000 psi. The factor of safety on number of cycles to produce failure would be even higher, extrapolation of the data from plate tests on a straight line gives a factor of safety of at least 3.0 on this basis.

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2. Stallmeyer, J. E., Nordmark, G. E., Munse, W. H., and Newmark, N. M., "Fatigue Strength of Welds in Low-Alloy Structural Steel," Supplement to the Welding Journal, June 1956.

3. Wilson, W. M., and Thomas, F. P., "Fatigue Tests of Riveted Joints," University of Illinois Engineering Experiment Station Bull. 302, 1938.

TABLE 1

CHEMICAL COMPOSITION OF BASE MATERIALS

Material	A7F*	A373	A441
C	0.20	0.23	0.20
Mn	0.28	0.63	1.14
P	0.009	0.022	0.015
S	0.041	0.031	0.031
Si	0.01	0.030	0.06
Cu	0.05	0.17	0.23
Va	-	-	0.06
Ni	0.01	-	-

*This material failed to meet the ASTM A7 tensile requirements.

TABLE 2

PHYSICAL PROPERTIES OF BASE MATERIALS

Material	A7F**	A373	A441
Yield Point, ksi *	30.3	38.8	61.6
Tensile Strength, ksi *	52.8	64.8	84.1
Elongation per 8 in., percent *	29.5	29.6	22.2

*Based on the average of three tests.

**This material failed to meet the ASTM A7 tensile requirements.

TABLE 3

STUD WELDING PROCEDURES

Specimens	Lift in.	Plunge in.	Weld Current Amps.	Arc Voltage Volts	Weld Time Cycles
GIA1 -GIA8	3/32	3/16	1500	33	58
GIB1 -GIB15	3/32	3/16	1500	33	58
GIB16-GIB20	3/32	3/16	1450	33	76
GIC1 -GIC5	3/32	3/16	1750	31	43
GID1 -GID10	3/32	3/16	1750	31	43

TABLE 4

FATIGUE RESULTS FOR GIA SPECIMENS
ZERO-TO-TENSION, AXIAL LOADING

Specimen	Stress Cycle ksi	Life Cycles
GIA1	0 to +16.5	1,320,000
GIA2	0 to +24.0	460,000
GIA3	0 to +24.0	840,000
GIA4	0 to +20.0	1,170,000
GIA5	0 to +16.5	1,480,000
GIA6	0 to +16.5	2,250,000
GIA7	0 to +15.0	3,240,000*

*Specimen did not fail.

TABLE 5

FATIGUE RESULTS FOR GIB SPECIMENS
ZERO-TO-TENSION, AXIAL LOADING

Specimen	Stress Cycle ksi	Life Cycles
GIB1	0 to +20.0	820,000
GIB2	0 to +16.5	1,460,000
GIB3	0 to +16.5	2,410,000
GIB4	0 to +15.5	2,510,000
GIB11 u	0 to +16.5	4,200,000
GIB12 u	0 to +20.0	2,060,000
GIB16 w	0 to +16.5	1,920,000
GIB17 w	0 to +16.5	1,610,000
GIB19 wr	0 to +28.0	4,940,000*
GIB19 wr	0 to +40.0	810,000
GIB20 wr	0 to +38.0	550,000

* Specimen did not fail.

r Studs were removed.

u Upsets were ground to form a smooth transition.

w Welding procedure altered.

TABLE 6

RESULTS OF FATIGUE TESTS OF GIB SPECIMENS
COMPLETE REVERSAL, AXIAL LOADING

Specimen	Stress Cycle ksi	Life Cycles
GIB5	-20.0 to +20.0	190,000
GIB6	-20.0 to +20.0	180,000
GIB7	-10.0 to +10.0	960,000
GIB8	- 8.5 to + 8.5	1,730,000
GIB9	- 8.5 to + 8.5	1,660,000

TABLE 7

RESULTS OF FATIGUE TESTS OF GIB SPECIMENS
ONE-HALF TENSION-TO-TENSION, AXIAL LOADING

Specimen	Stress Cycle ksi	Life Cycles
GIB13	+14.0 to +28.0	1,950,000
GIB14	+14.0 to +28.0	2,560,000
GIB15	+14.0 to +28.0	2,140,000
GIB18 w	+14.0 to +28.0	2,690,000

w Welding procedure altered.

TABLE 8

RESULTS OF FATIGUE TESTS OF GIC SPECIMENS
ONE-HALF TENSION-TO-TENSION, AXIAL LOADING

Specimen	Stress Cycle ksi	Life Cycles
GIC1	+27.9 to +55.8	280,000
GIC2	+14.0 to +28.0	2,220,000
GIC3	+14.0 to +28.0	2,700,000
GIC4	+14.0 to +28.0	2,590,000

TABLE 9

RESULTS OF FATIGUE TESTS ON GID SPECIMENS
ONE-HALF TENSION-TO-TENSION, AXIAL LOADING

Specimen	No. of Studs	Stress Cycle ksi	Life Cycles
GID1	1	+14.0 to +28.0	3,260,000*
GID1	1	+15.0 to +30.0	1,730,000
GID2	1	+14.0 to +28.0	2,710,000
GID3	1	+15.0 to +30.0	1,840,000
GID4	3	+14.0 to +28.0	1,630,000
GID5	3	+14.0 to +28.0	1,900,000
GID6	3	+14.0 to +28.0	1,890,000
GID7	5	+14.0 to +28.0	1,410,000
GID8	5	+14.0 to +28.0	1,880,000
GID9	5	+14.0 to +28.0	1,570,000
GID10	5	+14.0 to +28.0	1,460,000

*Specimen did not fail

TABLE 10

EFFECT OF VARIOUS STRESS RAISERS ON
FATIGUE LIFE OF PLATE SPECIMENS

ZERO-TO-TENSION, AXIAL LOADING

Specimen	$F_{2,000,000}$
Plain Plate (A441)	0 to +40 ksi
Plain Plate (A7)	0 to +35 ksi
Double V Butt Weld (A441)	0 to +28 ksi
Plate with Hole (A441)	0 to +24 ksi
Plate with Stud (A441)	0 to +16 ksi

TABLE 11

RESULTS OF STATIC TESTS

Specimen	ASTM Designation	Yield Point ksi	Ultimate Strength ksi
GIA7	A7F*	31.6	53.9
GIA8	A7F*	29.6	53.6
GIB10	A441	-	80.4

*Failed to meet the ASTM A7 tensile requirements.

TABLE 12

FATIGUE RESULTS FOR BEAM SPECIMENS
ONE-HALF TENSION-TO-TENSION, FLEXURAL LOADING

Specimen	Type*	Stress Cycle ksi	Life Cycles
GIE1	PB	+15.0 to +29.9	2,780,000
GIE2	PB	+16.4 to +32.8	2,070,000
GIE3	PB	+16.5 to +32.9	1,940,000
GIE4	SF	+11.5 to +24.2	2,020,000
GIE5	SF	+12.4 to +24.6	2,210,000
GIE6	SF	+12.7 to +25.2	1,830,000
GIE7	RC	+10.7 to +21.4** +15.0 to +30.0**	1,480,000 610,000
GIE8	RC	+15.0 to +30.0**	1,640,000
GIE9	RC	+15.3 to +30.0**	1,500,000

* PB - plain beam
SF - stud flexors
RC - reinforced concrete

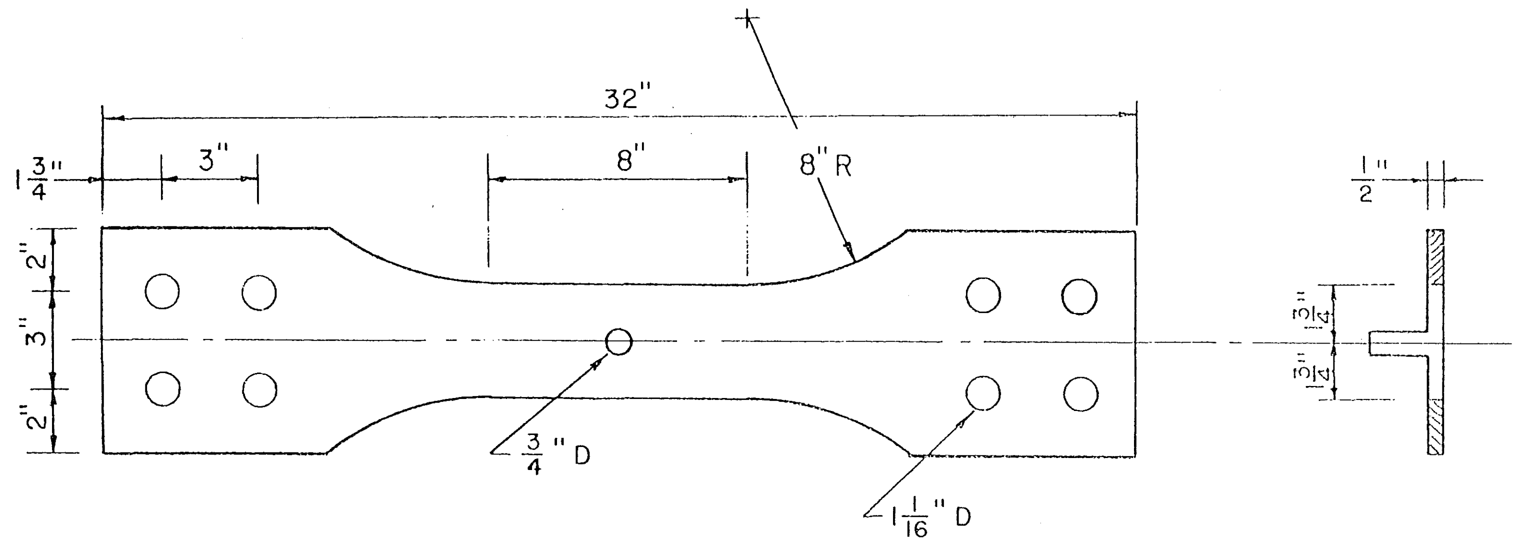
** Based on $\frac{Mc}{I}$ where I assumes the concrete to be cracked.

TABLE 13

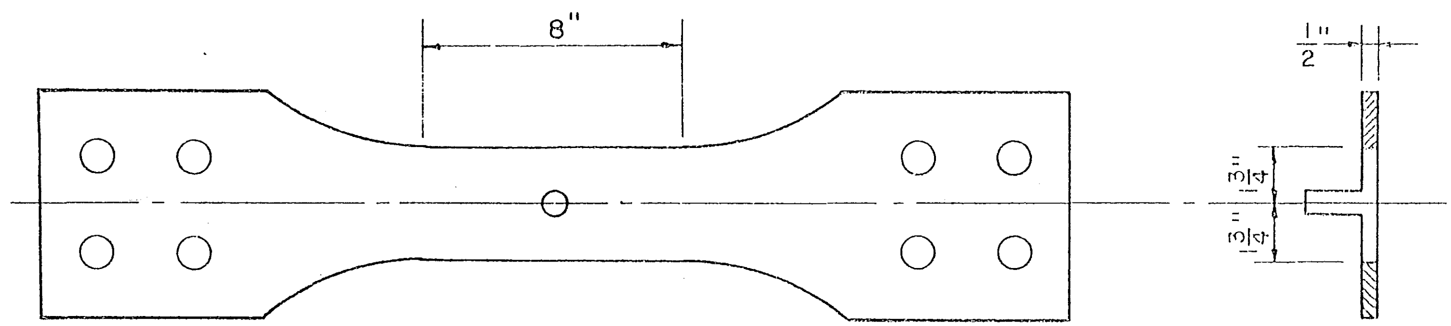
EFFECT OF STUD WELDING PROCEDURE

Specimen	GIA2	GIB1	GIB16	GIC5
Type of Steel	A7F	A441	A441	A441
Heat Input*				
Weld Current (amperes)	1500	1500	1450	1750
Arc Voltage (volts)	33	33	33	31
Weld Time (cycles)	58	58	76	43
Heat (KVA cycles)	2870	2870	3630	2330
Zone Widths (mm)				
Heat-Affected Zone Stud	3.0	1.5	2.5	1.5
Weld Metal	1.5	2.5	5.0	2.0
Heat-Affected Zone Plate	1.0	1.5	2.5	1.0
Average Zone Hardness (Knoop)				
Base Metal Stud	180	171	195	157
Heat-Affected Zone Stud	181	179	184	169
Weld Metal	143	255	266	237
Heat-Affected Zone Plate	194	248	283	305
Base Metal Plate	150	222	228	215

*In all cases a lift of 3/32" and a plunge of 3/16" were used.

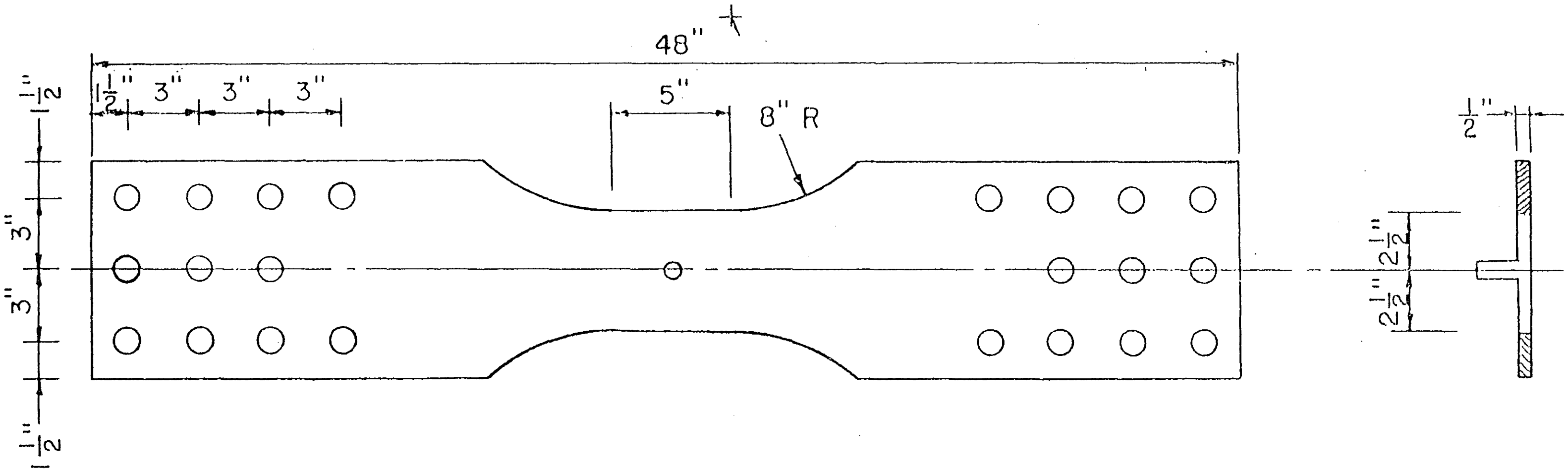


(a) GIA Specimens

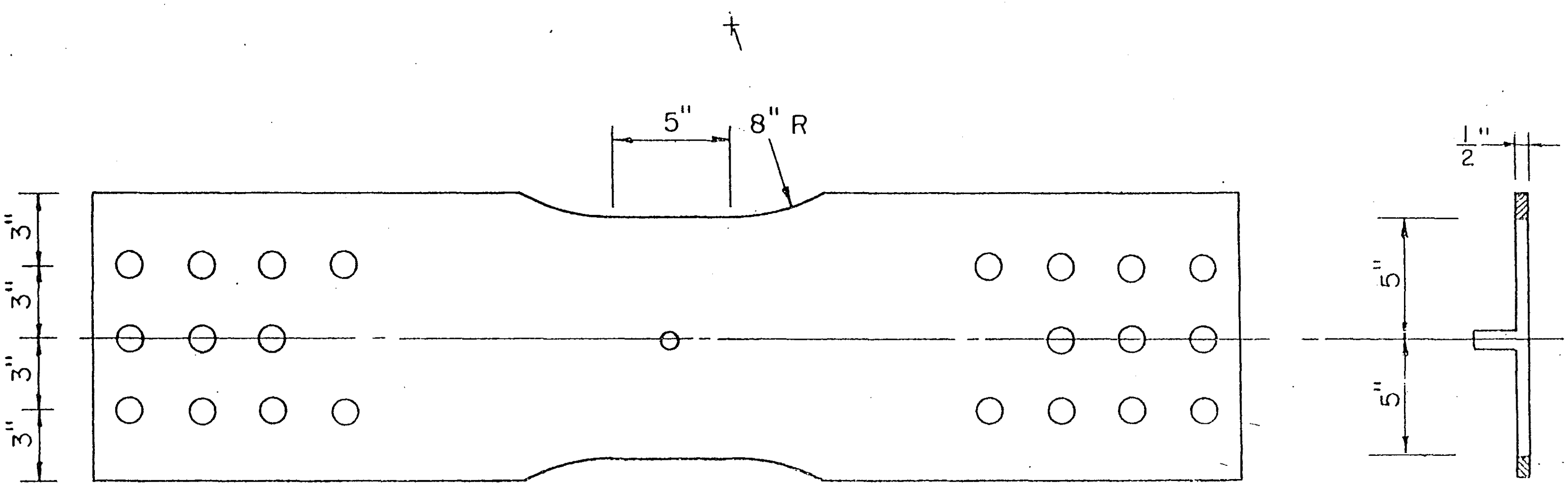


(b) GIB Specimens

FIG. I DIMENSIONS OF SMALL PLATE SPECIMENS

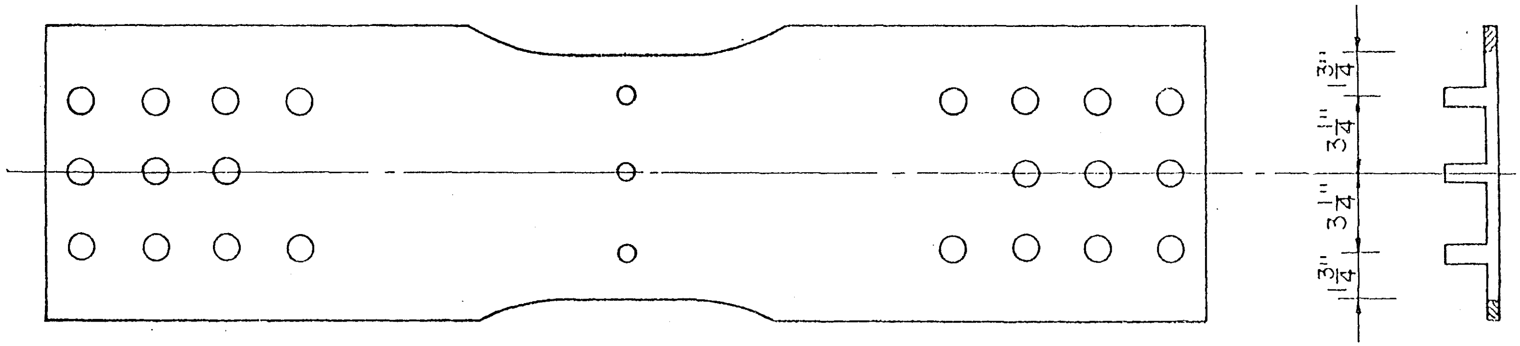


(a) GIC Specimens

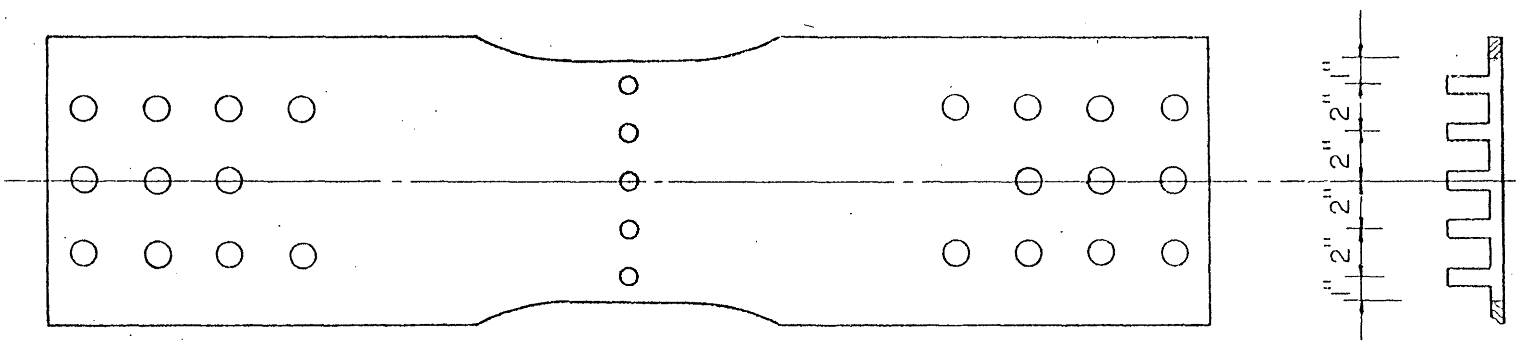


(b) Specimens GID1 Thru GID3

FIG. 2 DIMENSIONS OF LARGE PLATE SPECIMENS WITH A SINGLE STUD



(a) Specimens GID 4 Thru GID 6



(b) Specimens GID 7 Thru GID 10

FIG. 3 DIMENSIONS OF LARGE PLATE SPECIMENS WITH MULTIPLE STUDS

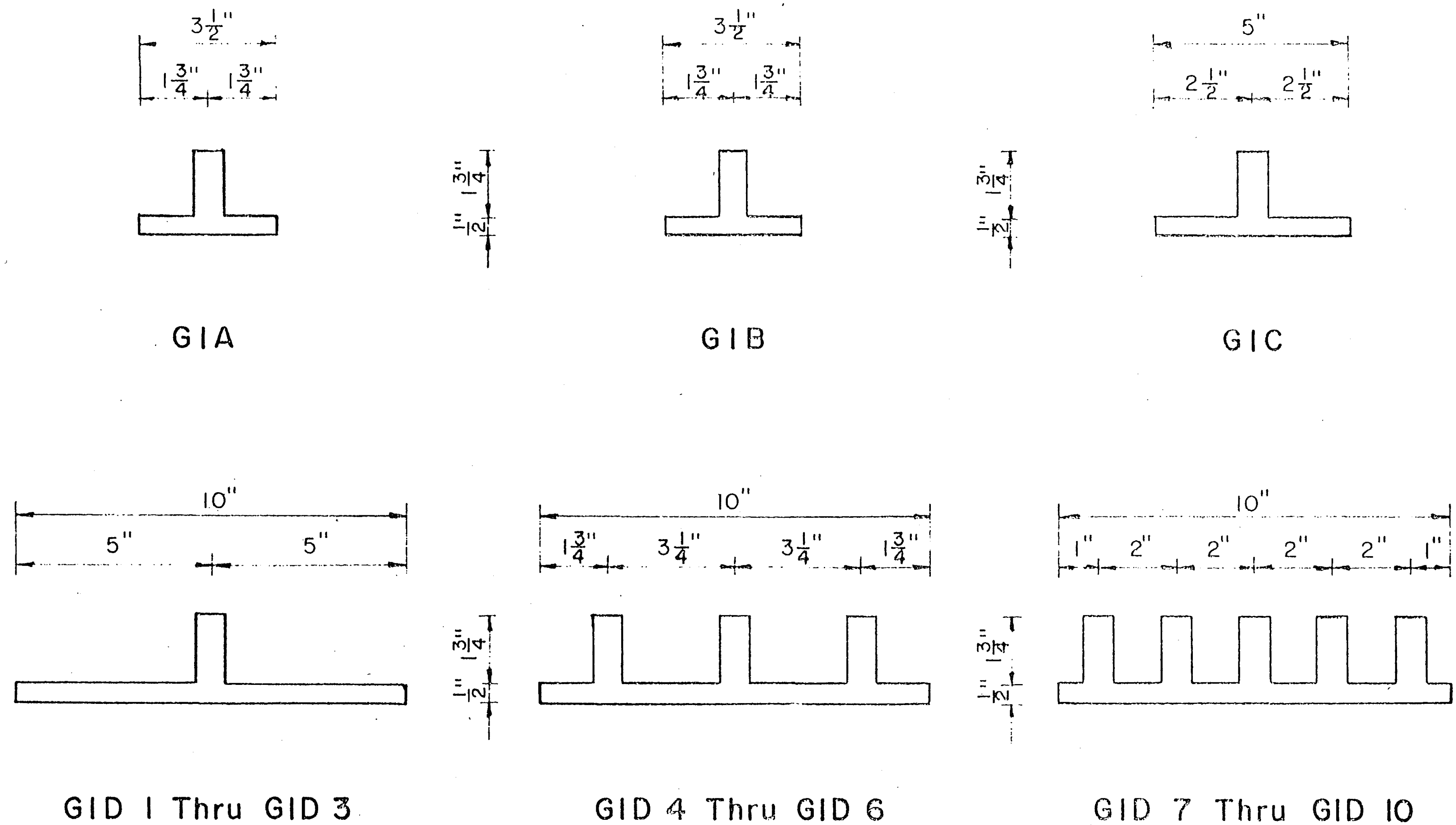
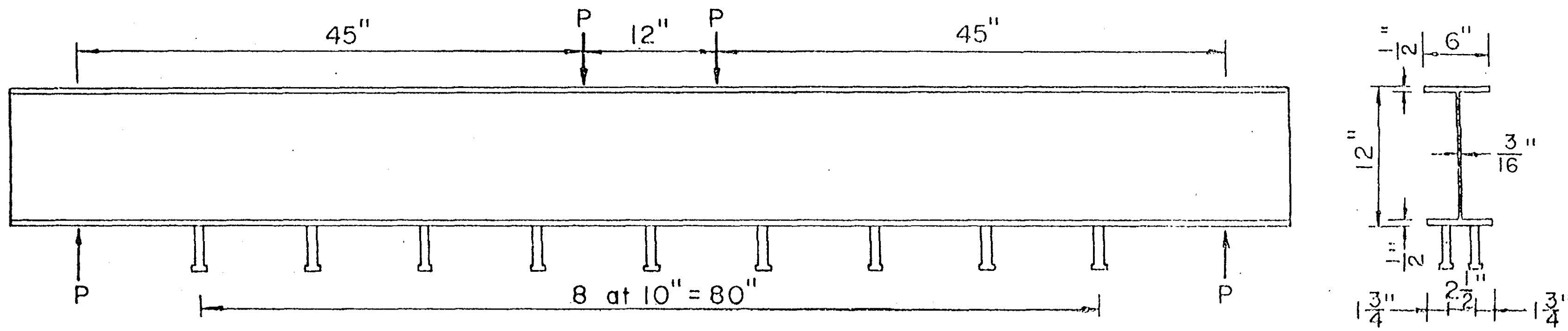
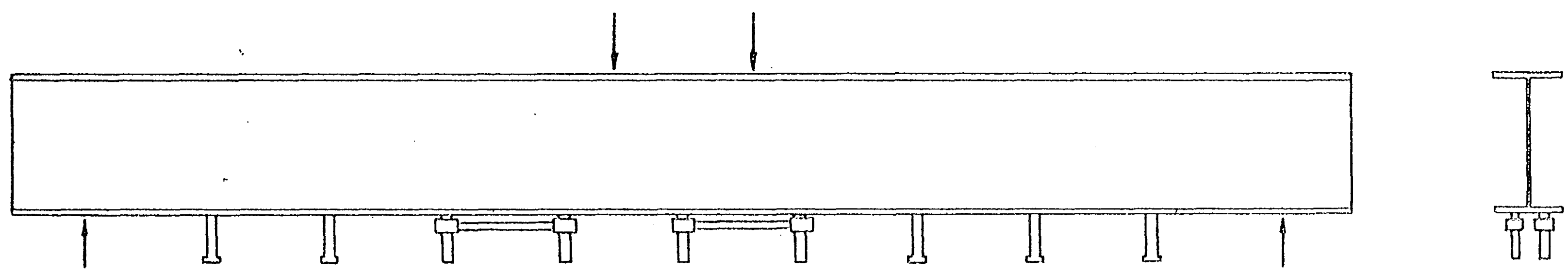


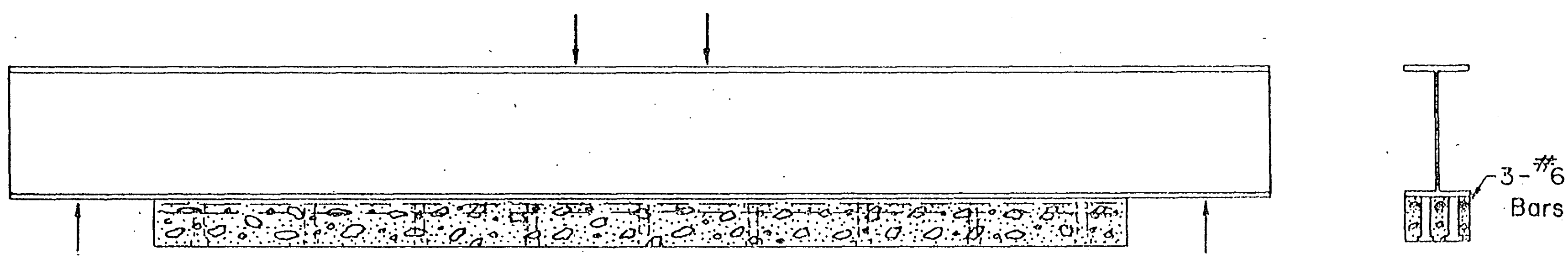
FIG. 4 CROSS-SECTIONS OF FLAT PLATE SPECIMENS THROUGH THE LINE OF STUDS



(a) Specimens GIE 1 Thru GIE 3



(b) Specimens GIE 4 Thru GIE 6



(c) Specimens GIE 7 Thru GIE 10

FIG. 5 DETAILS OF BEAM SPECIMENS

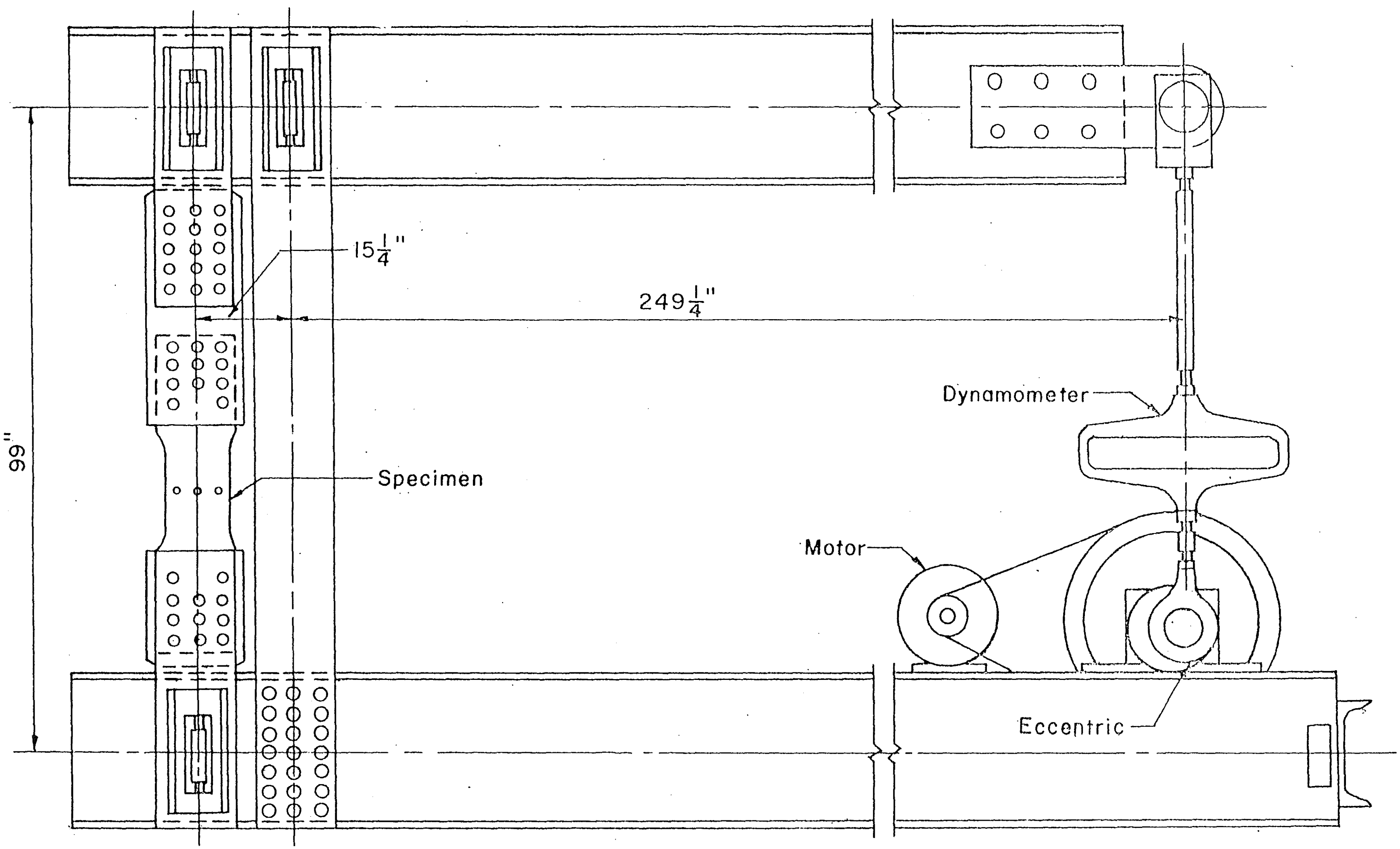


FIG. 6 ILLINOIS' FATIGUE TESTING MACHINE FOR AXIAL LOADING

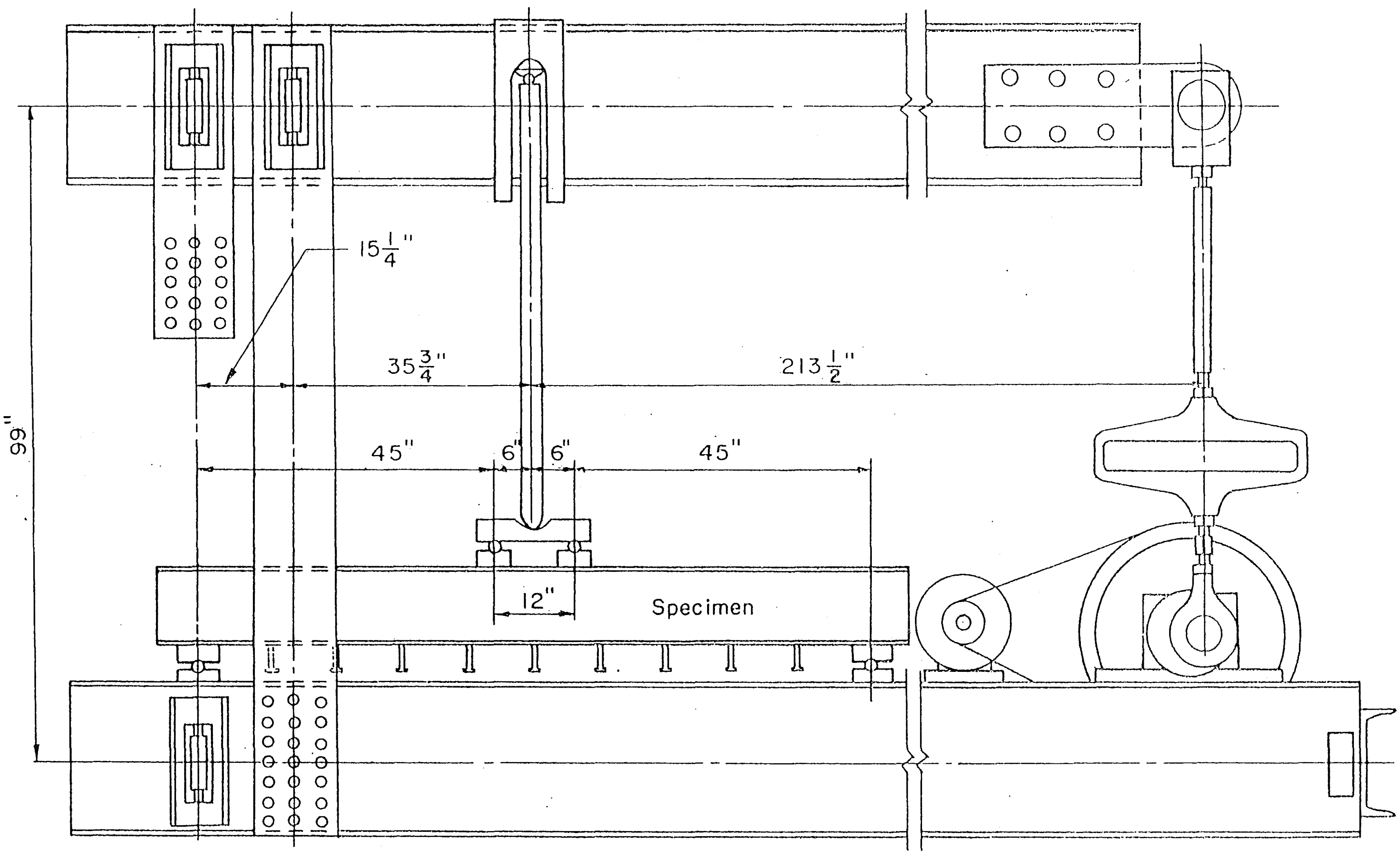


FIG. 7 ILLINOIS' FATIGUE TESTING MACHINE MODIFIED FOR FLEXURAL LOADING

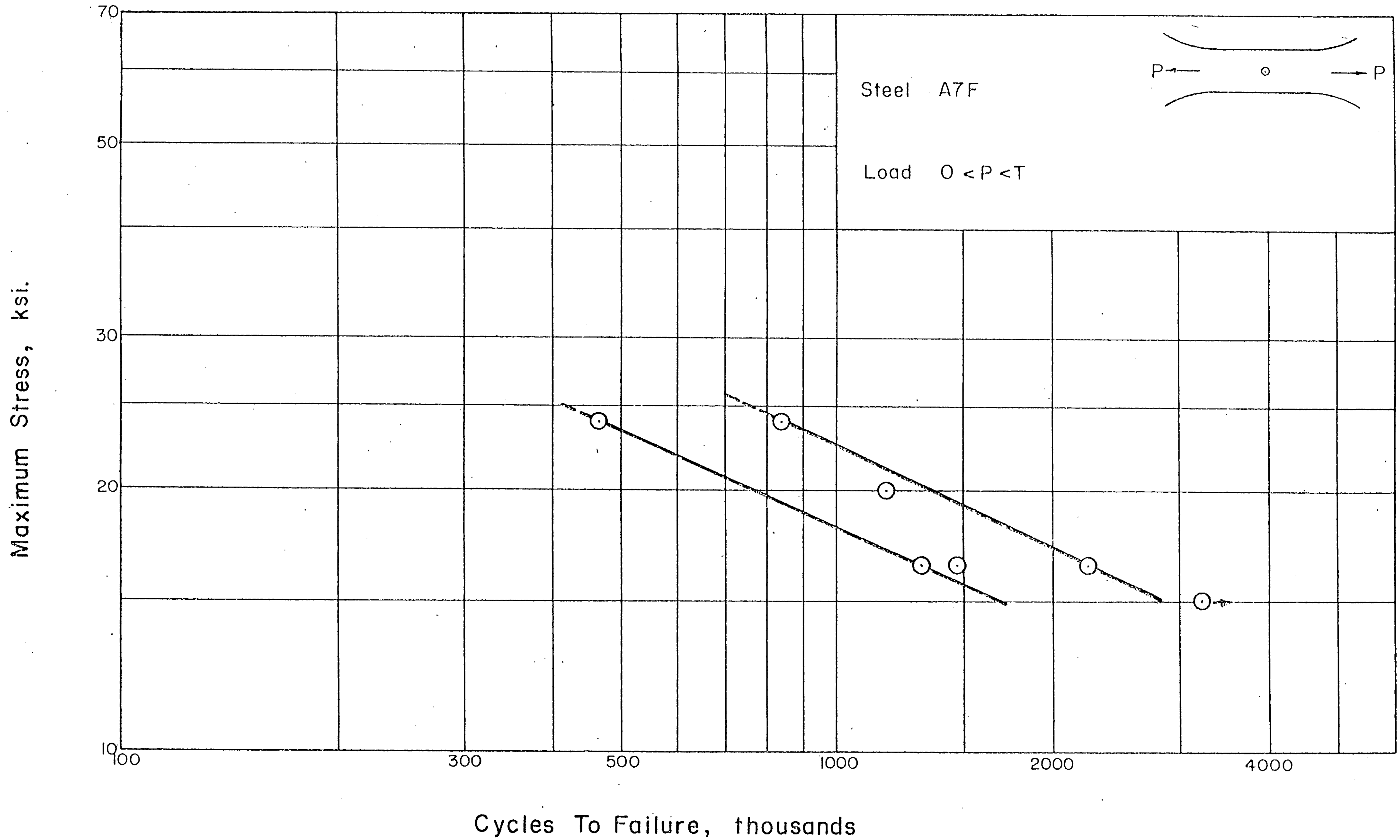


FIG. 8 FATIGUE RESULTS FOR GIA SPECIMENS ZERO-TO-TENSION STRESS CYCLE

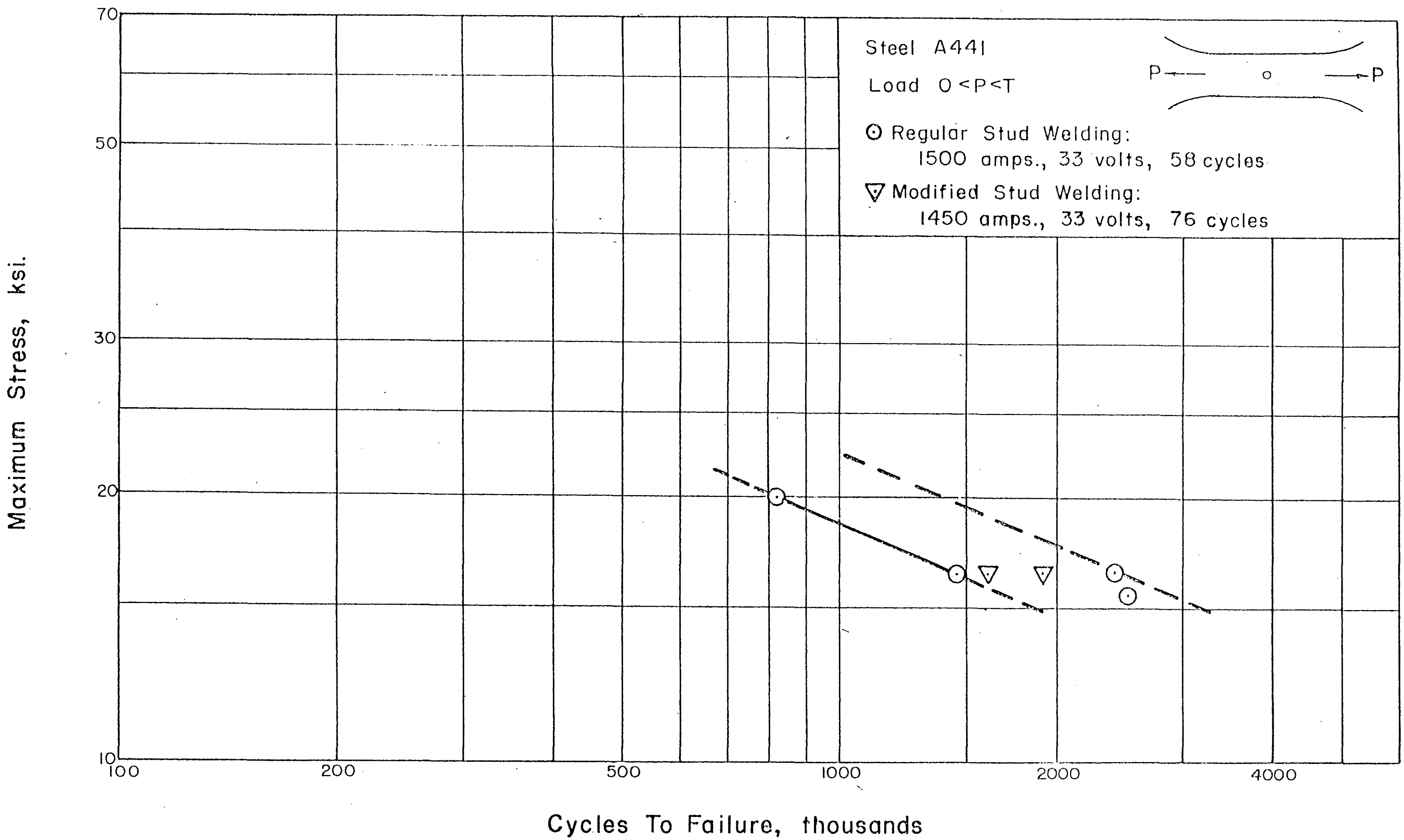


FIG. 9 FATIGUE RESULTS FOR GIB SPECIMENS ZERO-TO-TENSION STRESS CYCLE

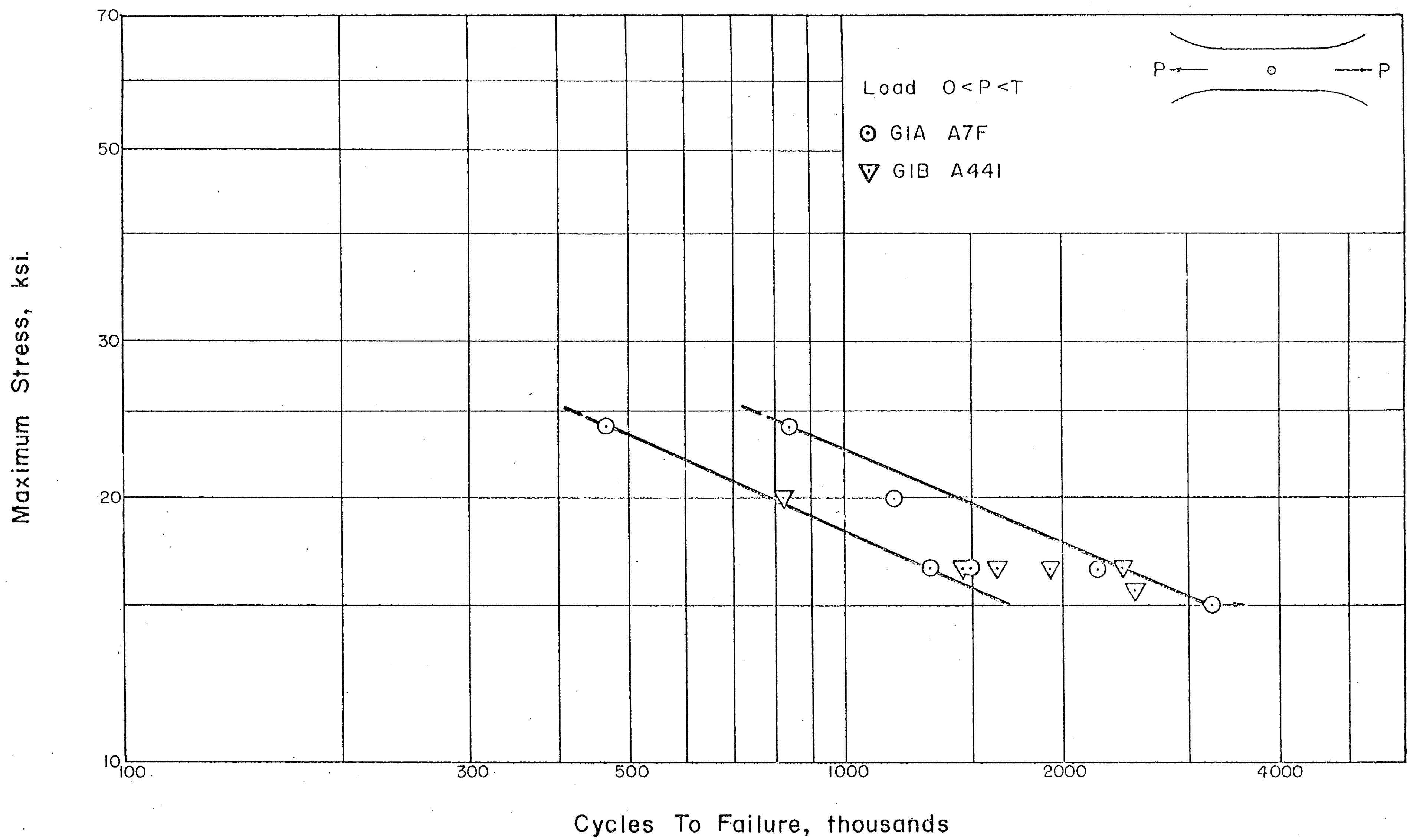


FIG. 10 EFFECT OF TYPE OF STEEL ON FATIGUE LIFE ZERO-TO-TENSION STRESS CYCLE

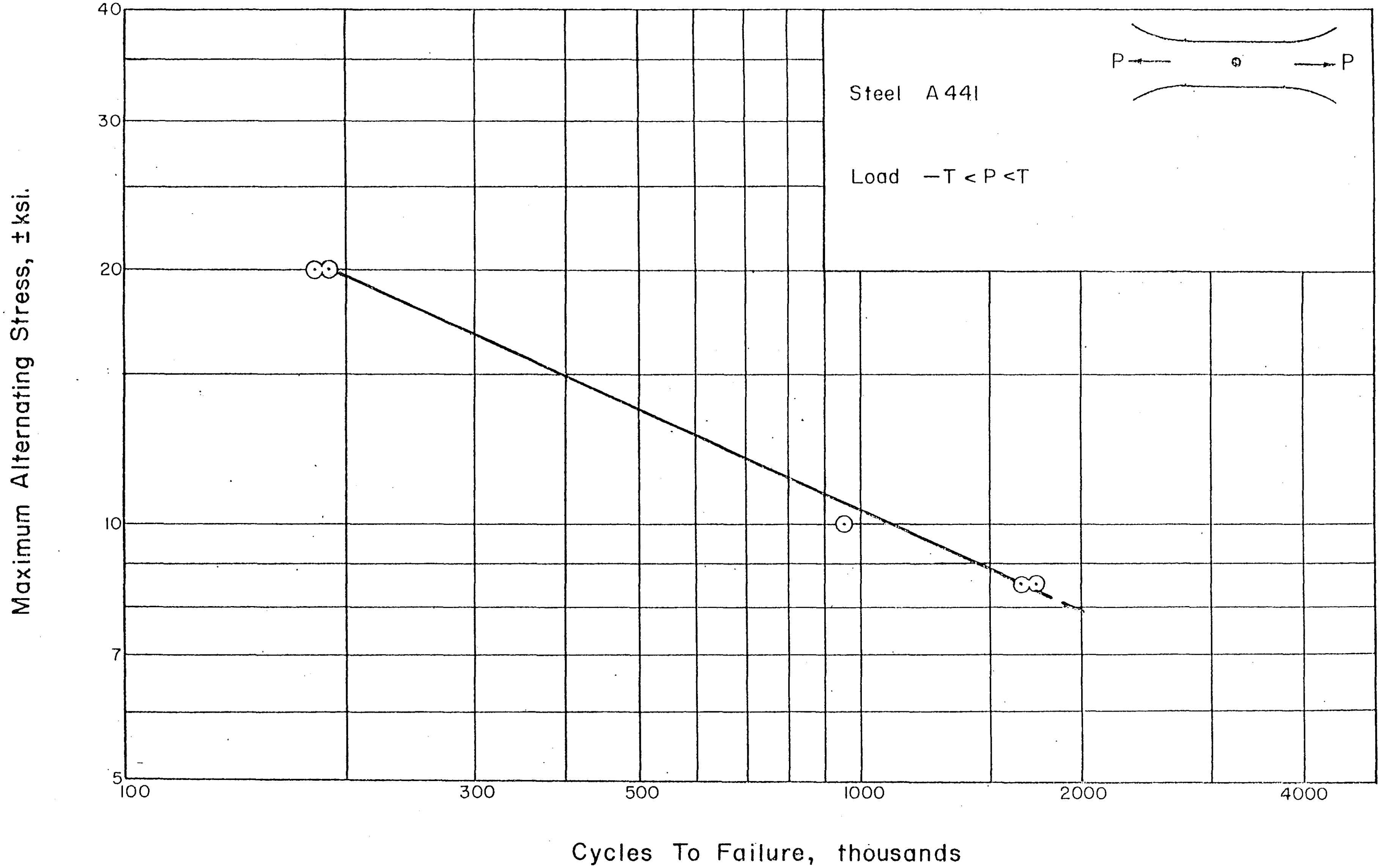


FIG. 11 FATIGUE RESULTS FOR GIB SPECIMENS COMPLETE REVERSAL STRESS CYCLE

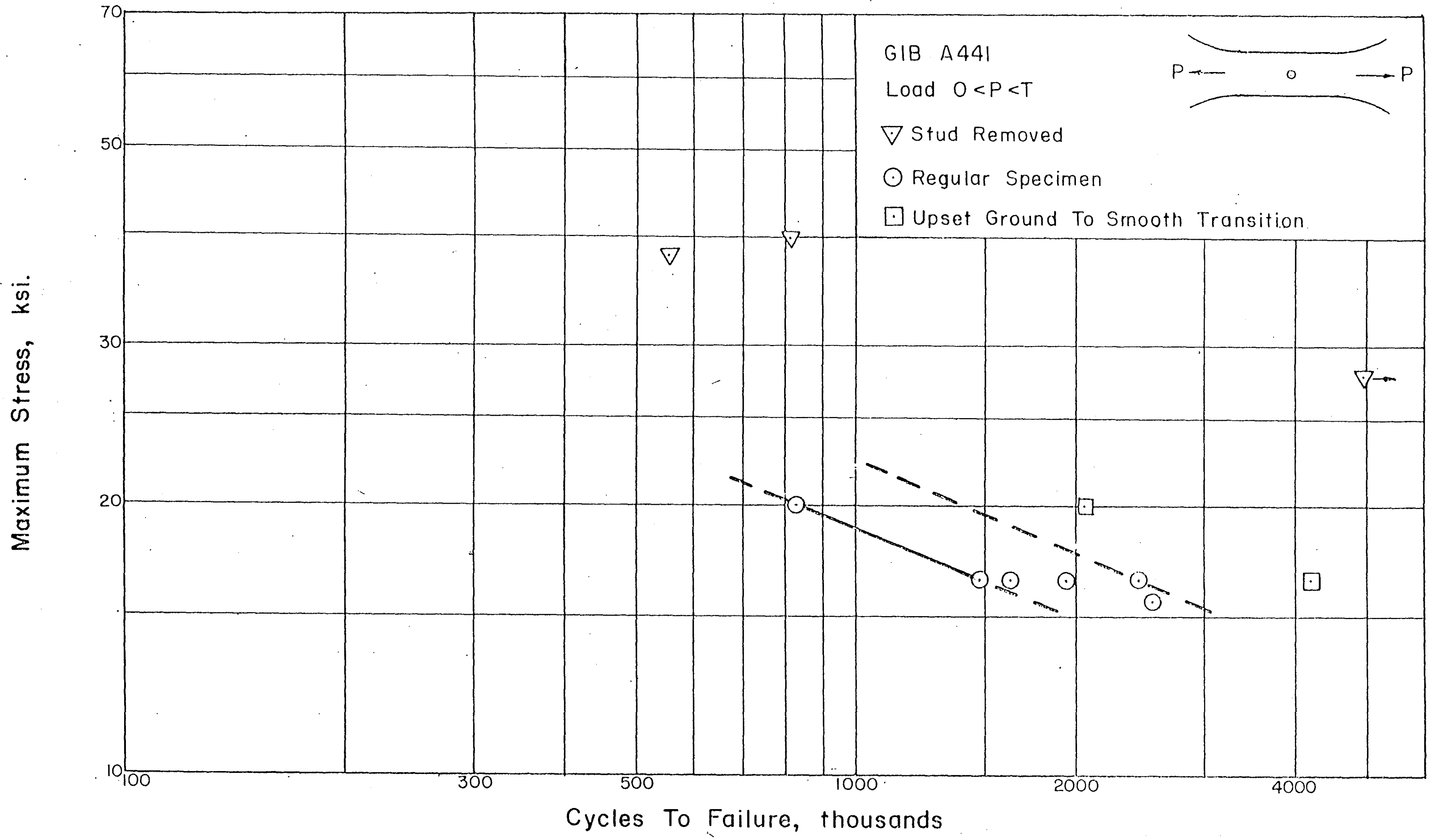


FIG. 12 GEOMETRICAL EFFECT ON FATIGUE RESULTS ZERO-TO-TENSION STRESS CYCLE

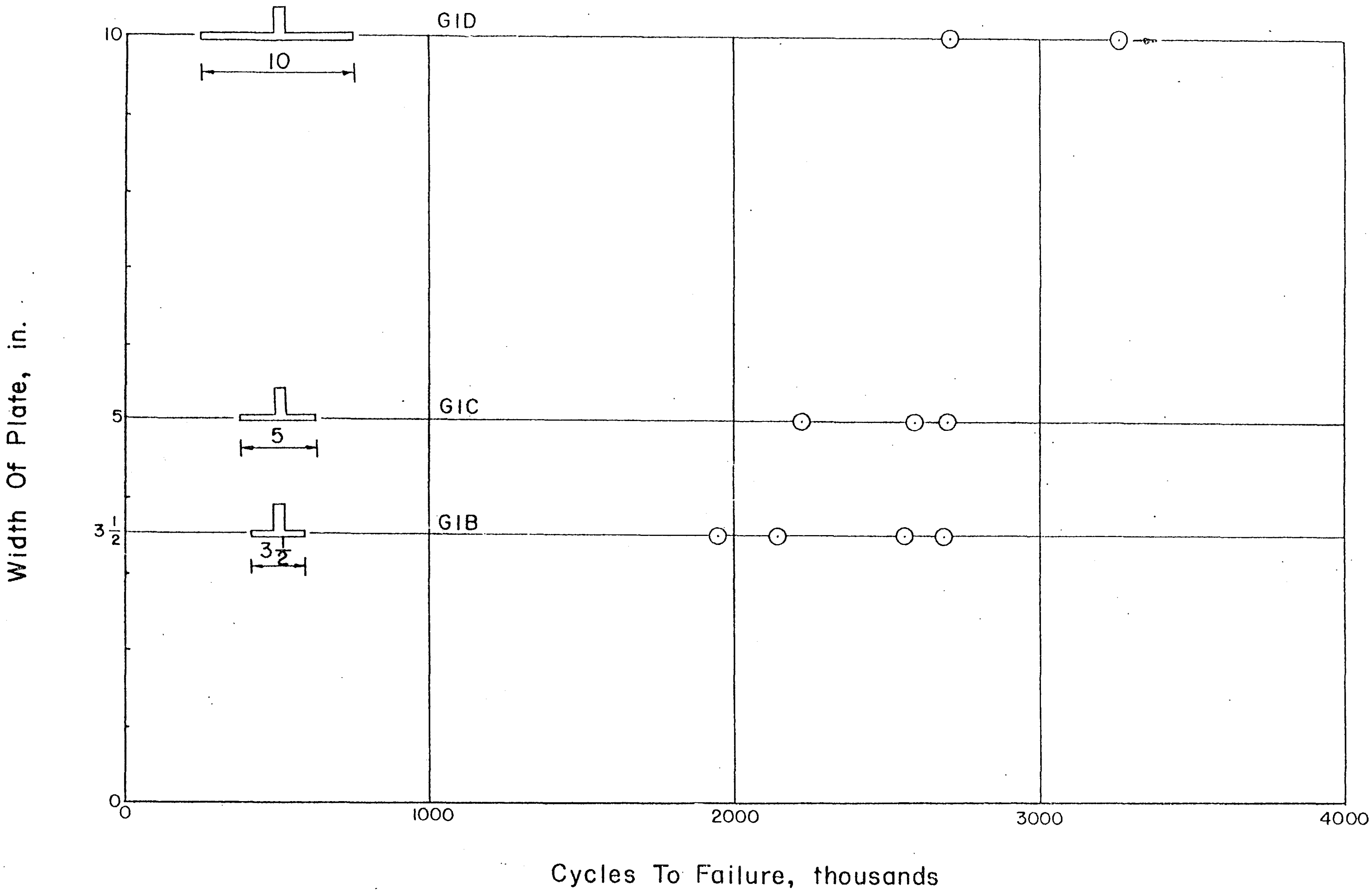


FIG. 13 WIDTH OF PLATE VERSUS FATIGUE LIFE STRESS CYCLE + 14.0 TO + 28.0 KSI.

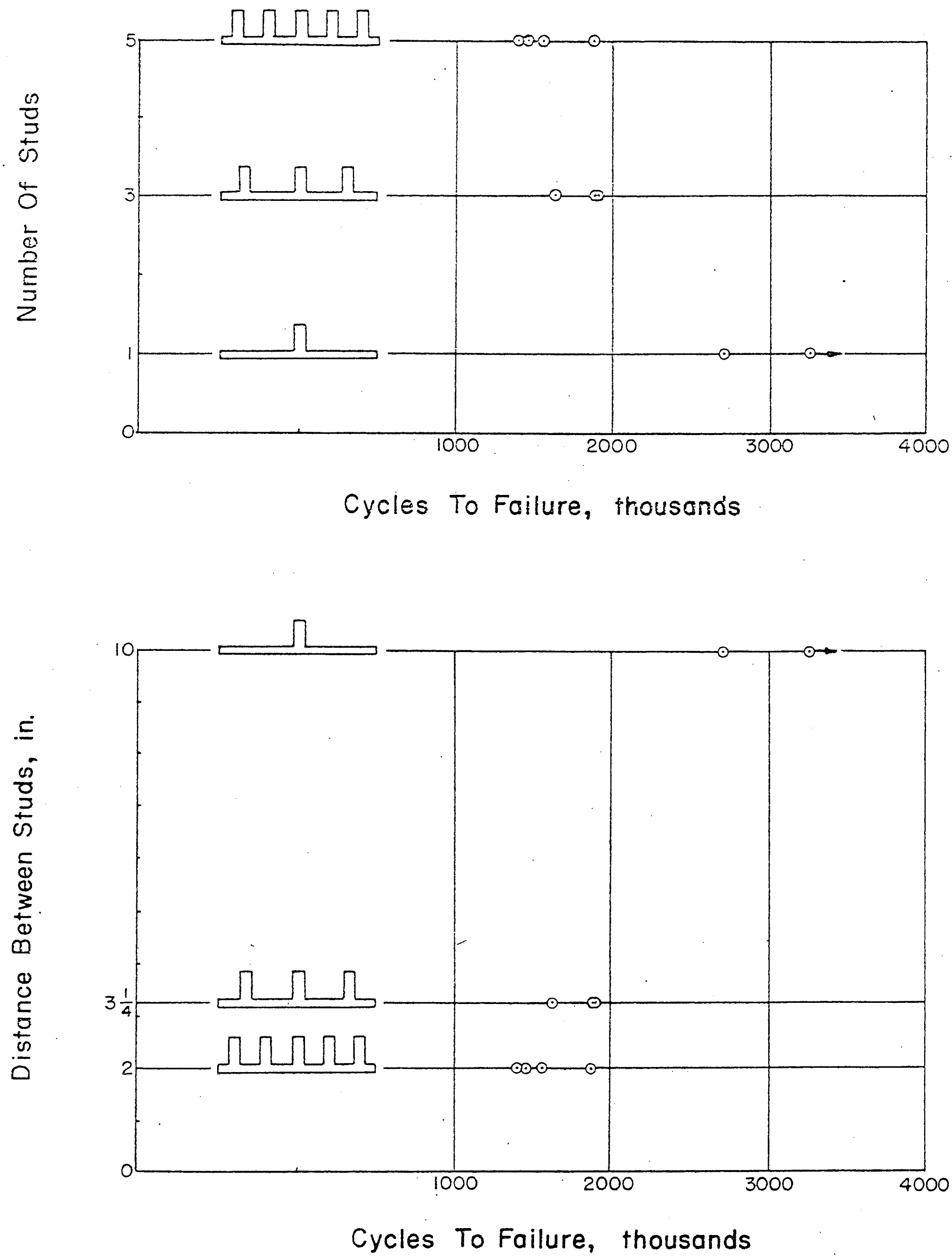
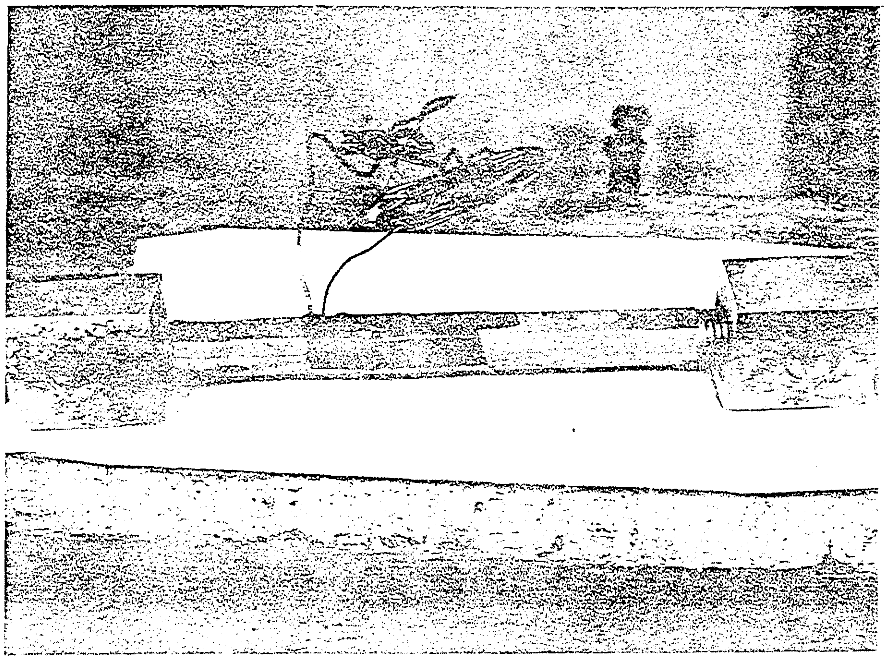
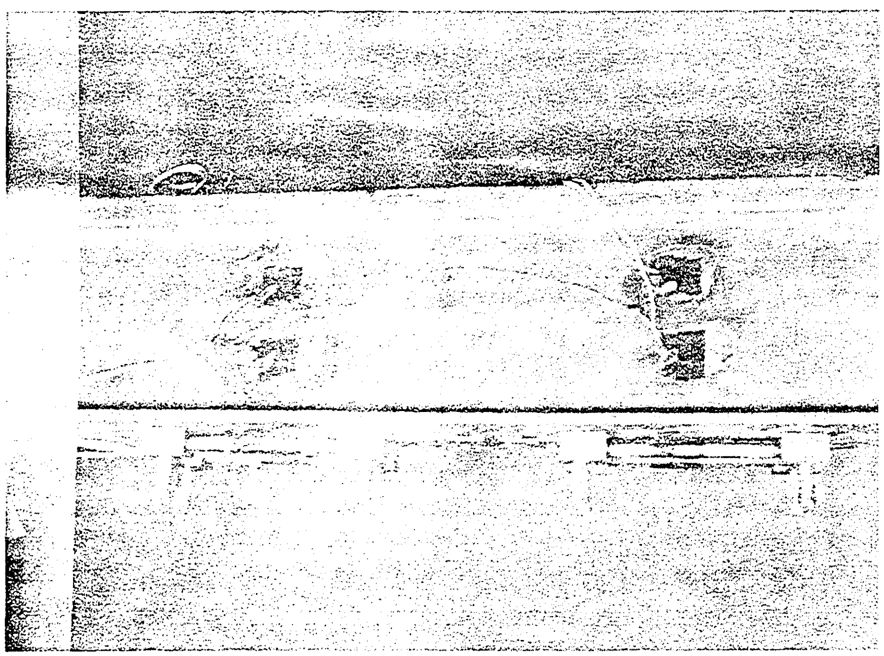


FIG. 14 STUD SPACING VERSUS FATIGUE LIFE
STRESS CYCLE +14.0 TO +28.0 KSI.

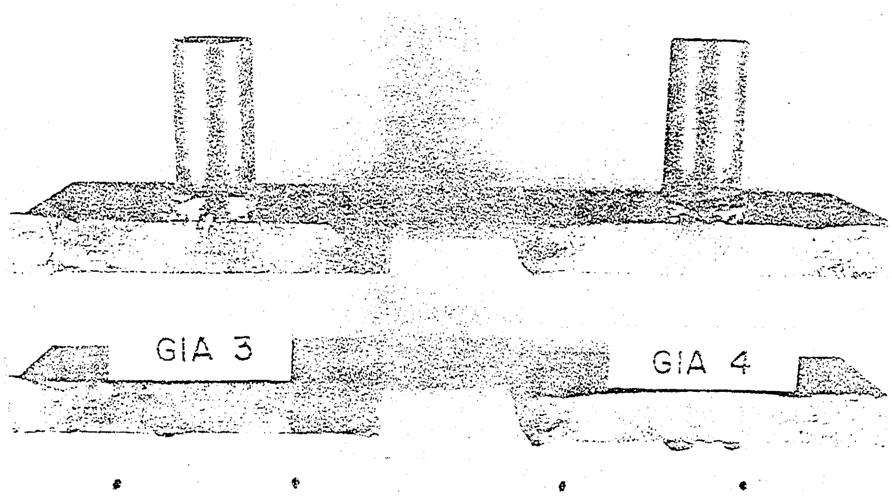


(a) Mechanical Stud Flexor

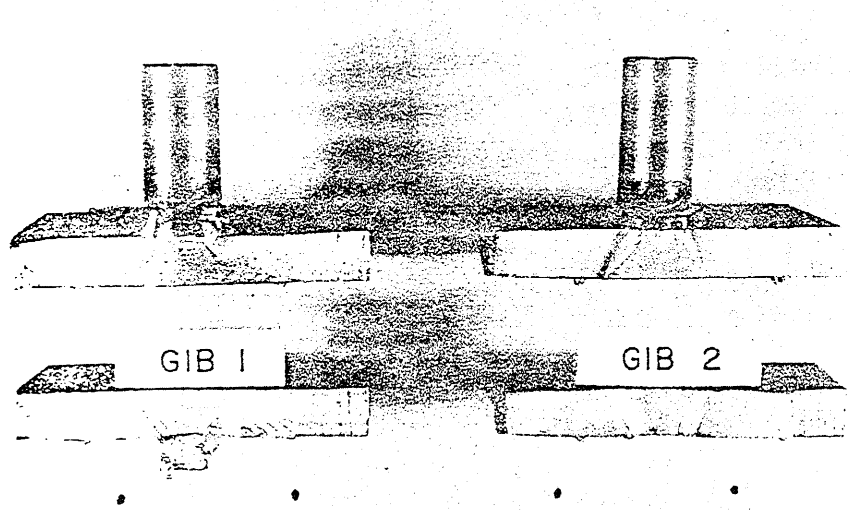


(b) Beam With Stud Flexors In Position

FIG. 15 PHOTOGRAPHS OF MECHANICAL STUD FLEXORS

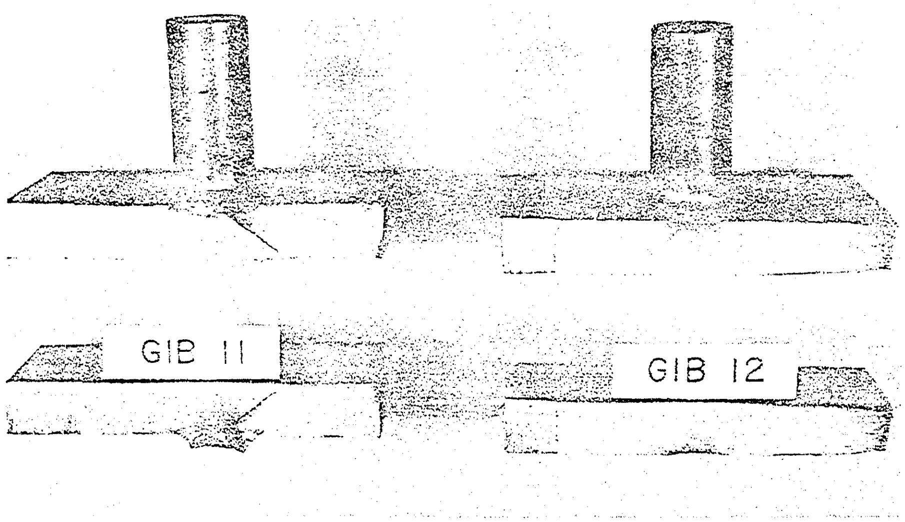


(a) Specimens Of A7F Steel

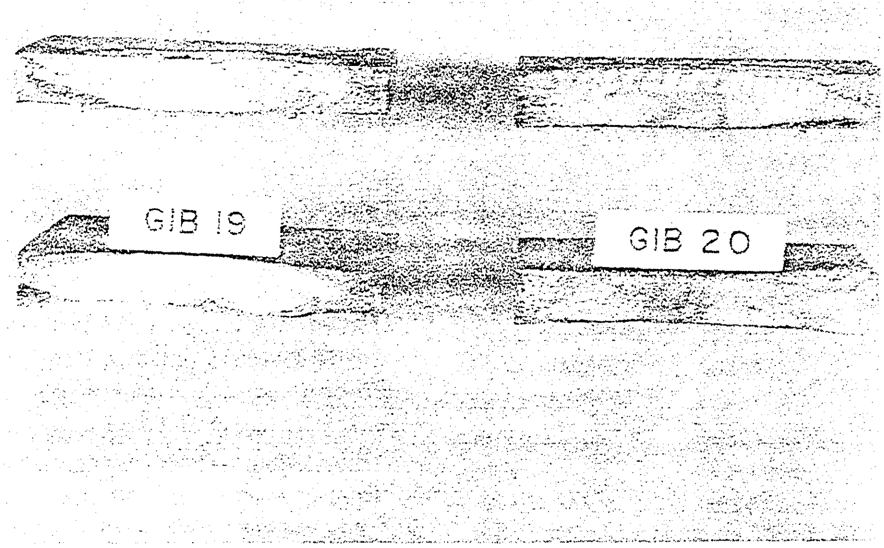


(b) Specimens Of A441 Steel

FIG. 16 TYPICAL FRACTURE SURFACES OF SINGLE STUD SPECIMENS

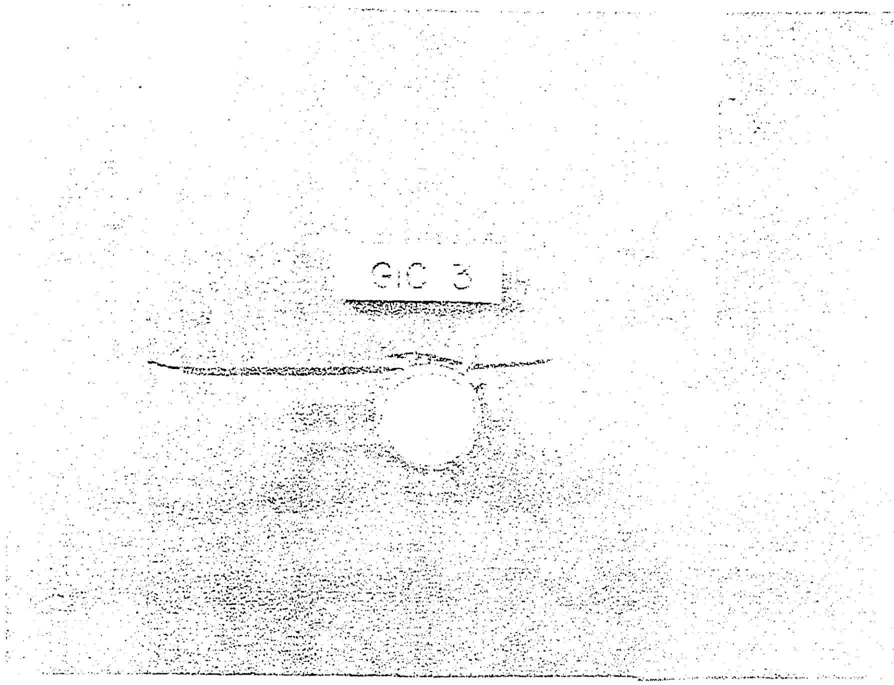


(a) Specimens With Ground Upset

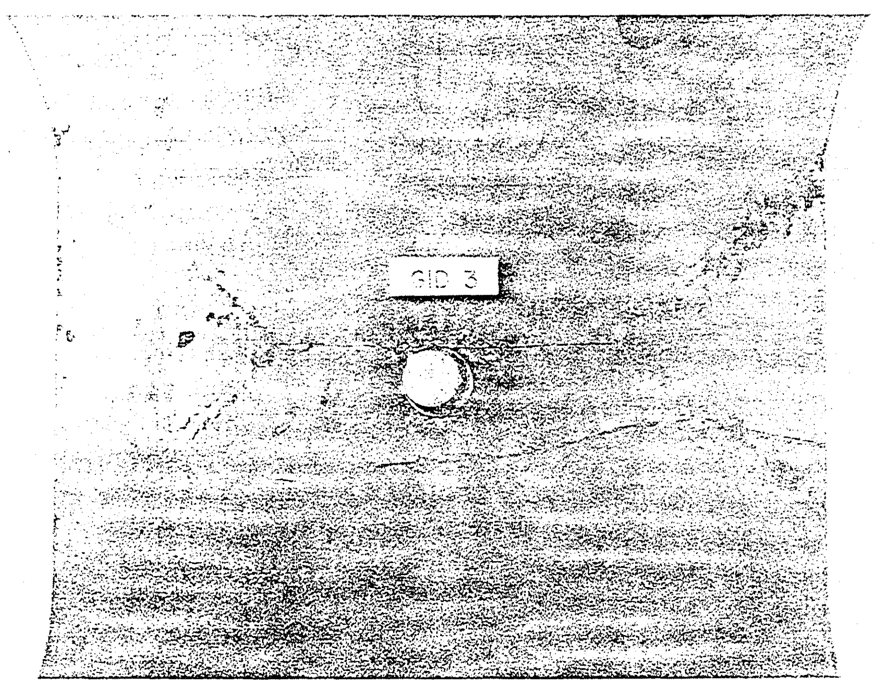


(b) Specimens With Stud Completely Removed

FIG. 17 FRACTURE SURFACES OF SPECIMENS WITH ALTERED GEOMETRY

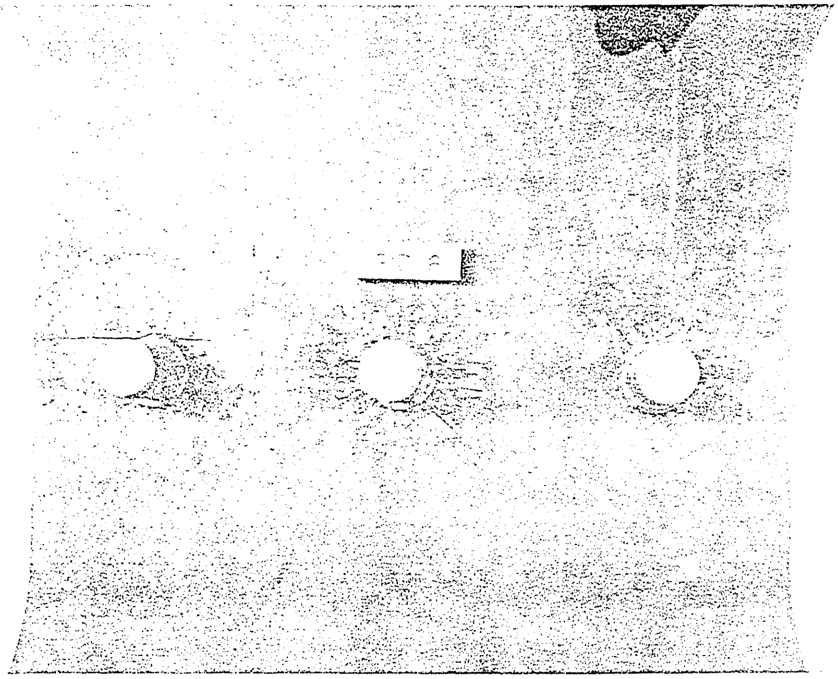


(a) Five-Inch Wide Specimen

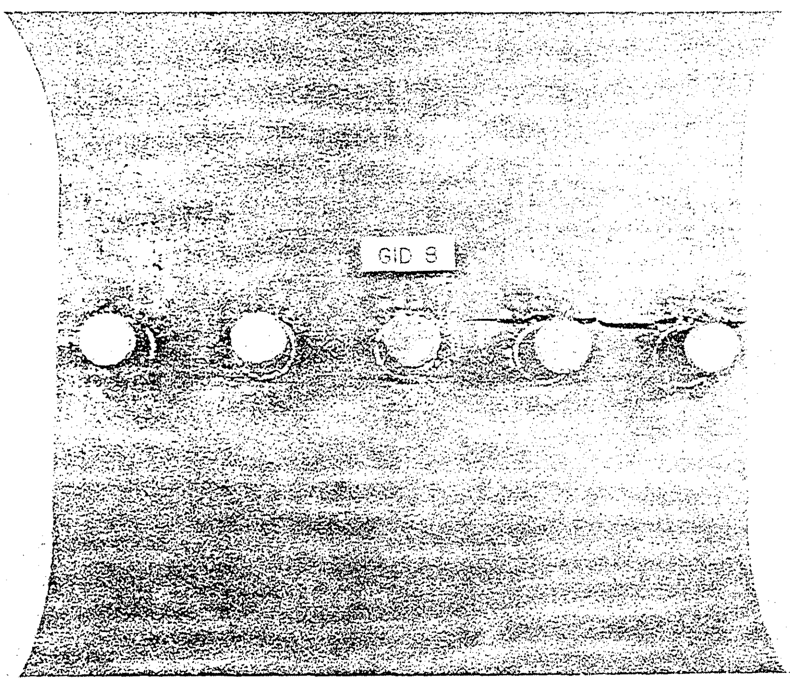


(b) Ten-Inch Wide Specimen

FIG. 18 FRACTURES OF SINGLE STUD WIDE PLATE SPECIMENS

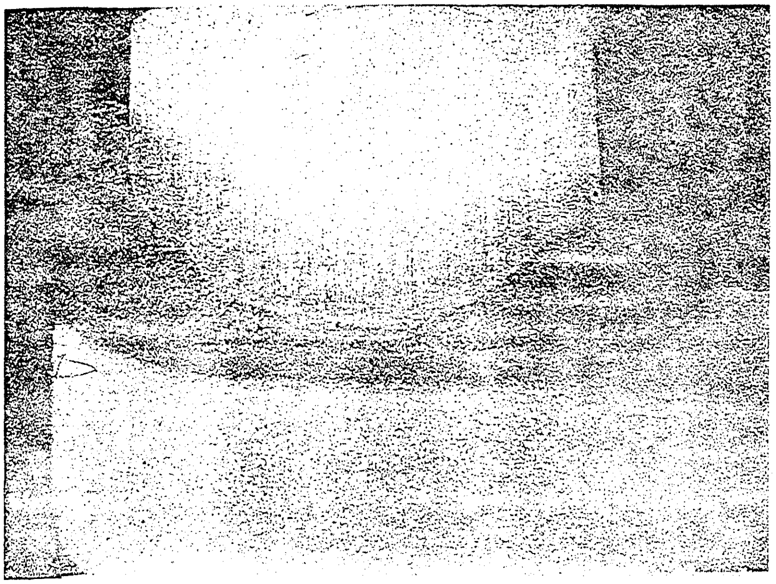


(a) Specimen With Three Studs

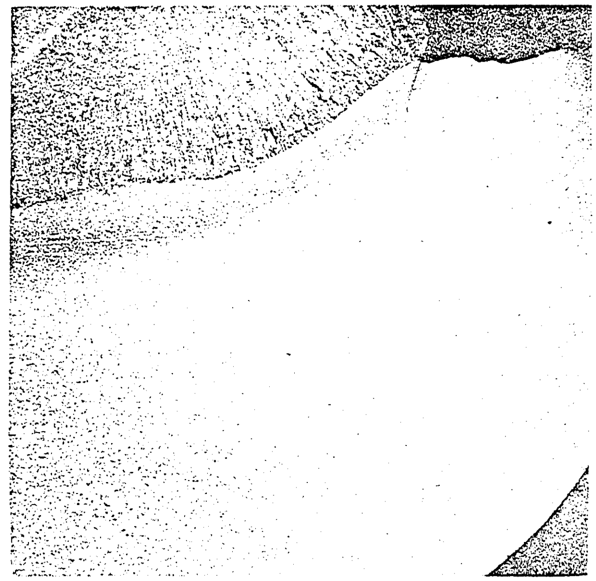


(b) Specimen With Five Studs

FIG. 19 FRACTURES OF MULTIPLE STUD WIDE PLATE SPECIMENS



Macrograph 3x

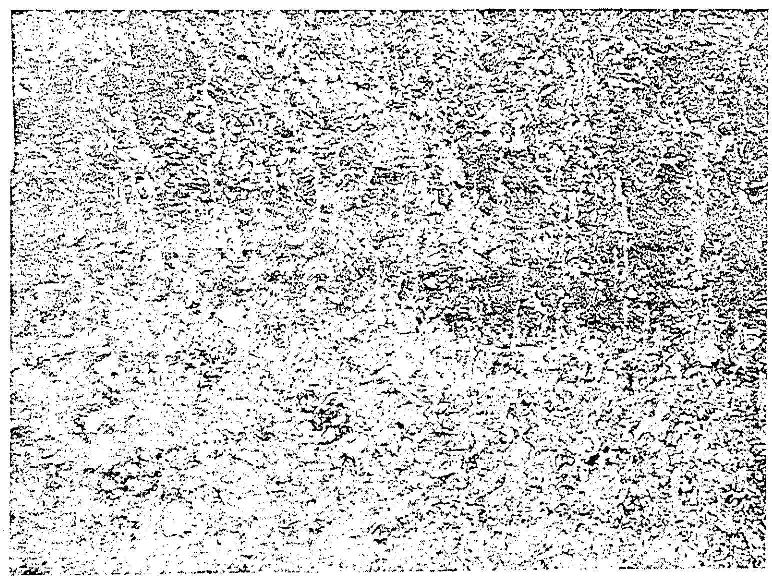


Macrograph 6x

72x

WM →

HABM →



72x

HABM →

BM →

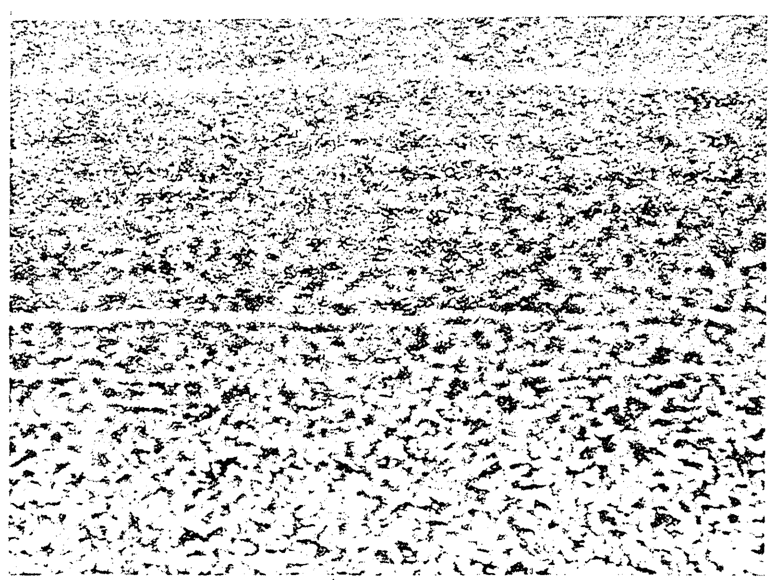
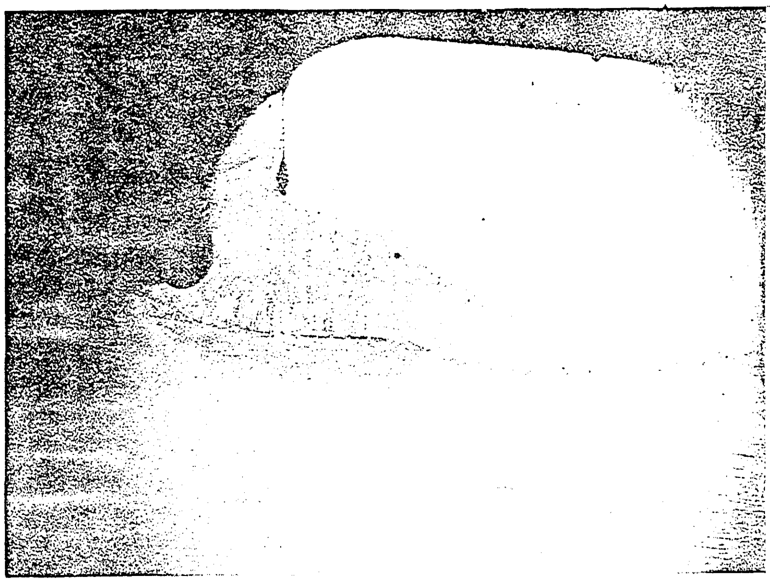


FIG. 20 MACROGRAPHS AND MICROGRAPHS OF SPECIMEN G1A2

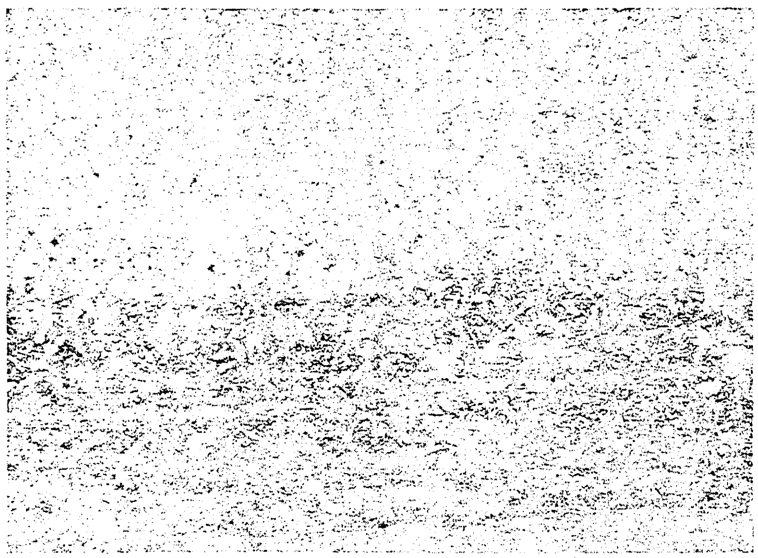


Macrograph 5x

72x

WM →

HABM →



72x

HABM →

BM →

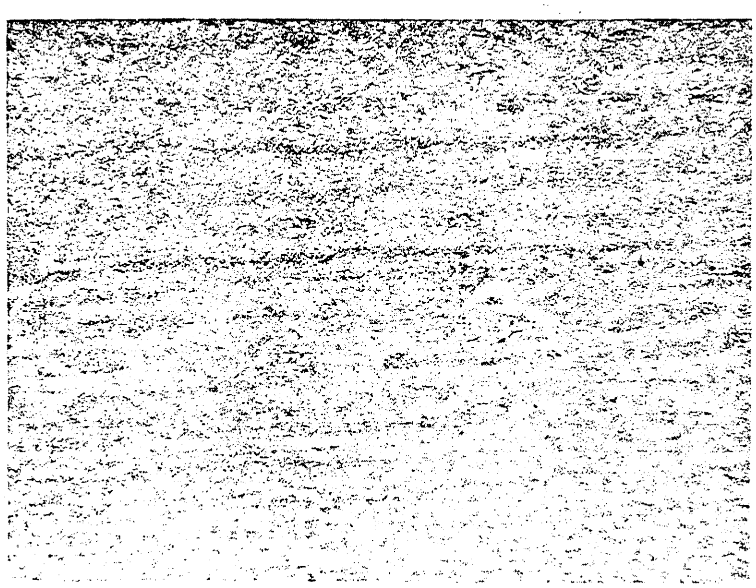
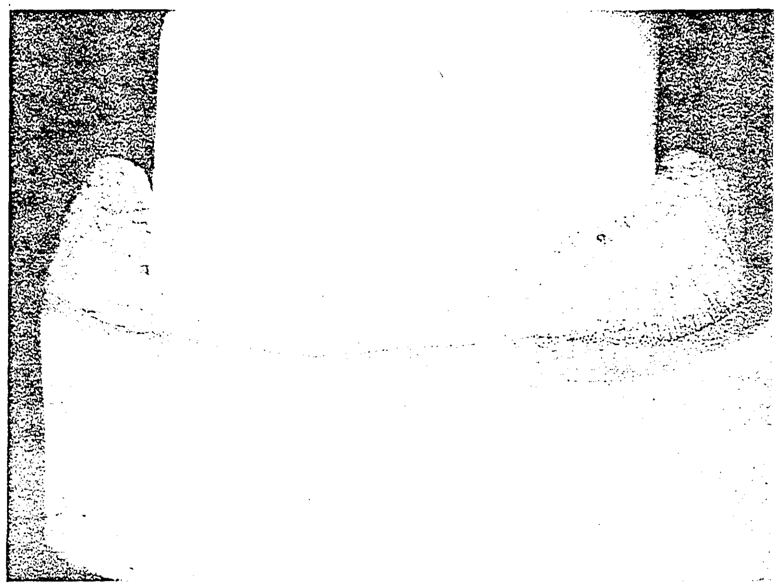


FIG. 21 MACROGRAPH AND MICROGRAPHS OF SPECIMEN G1B1



Macrograph 3x

75x

WM →

HAZ →

75x

HAZ →

BM →

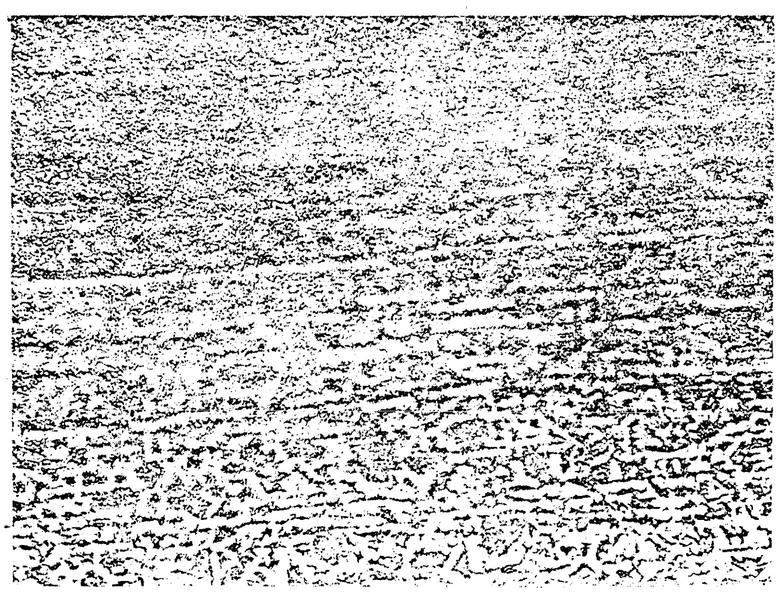
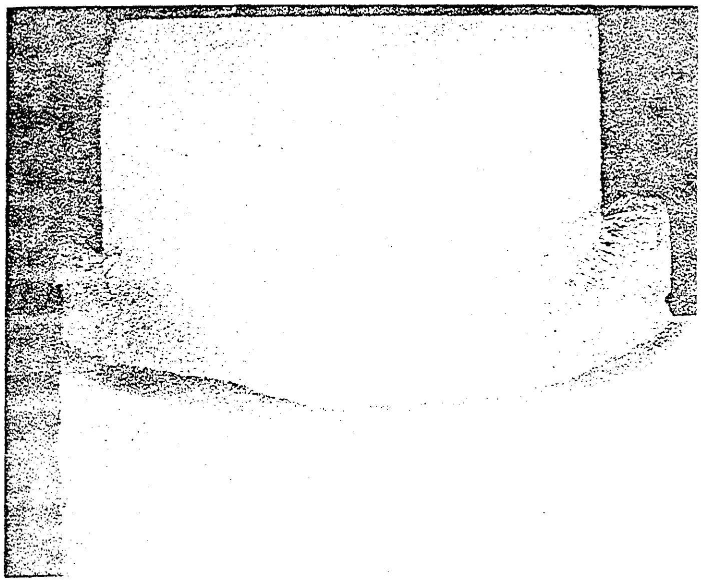


FIG. 22 MACROGRAPH AND MICROGRAPHS OF SPECIMEN G1B16



Macrograph 3x

Crack In HAZ 500x

75x

WM ——→

HAZ ——→

75x

HAZ ——→

BM ——→

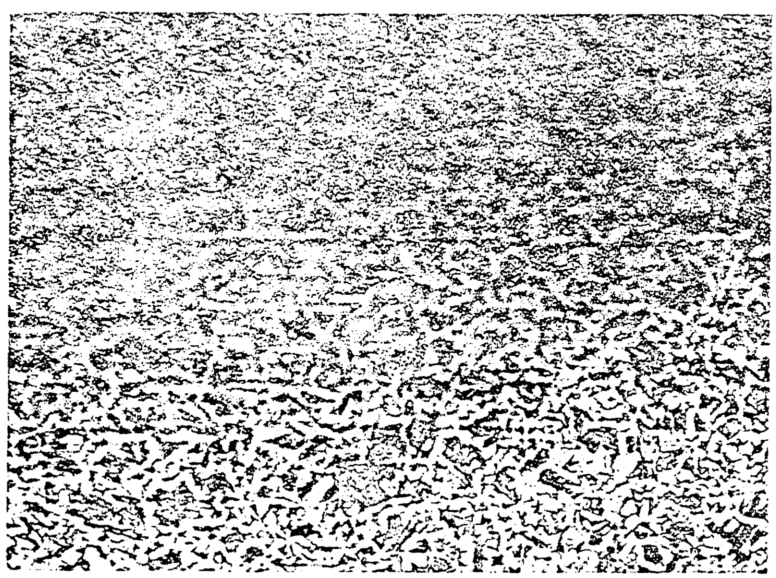
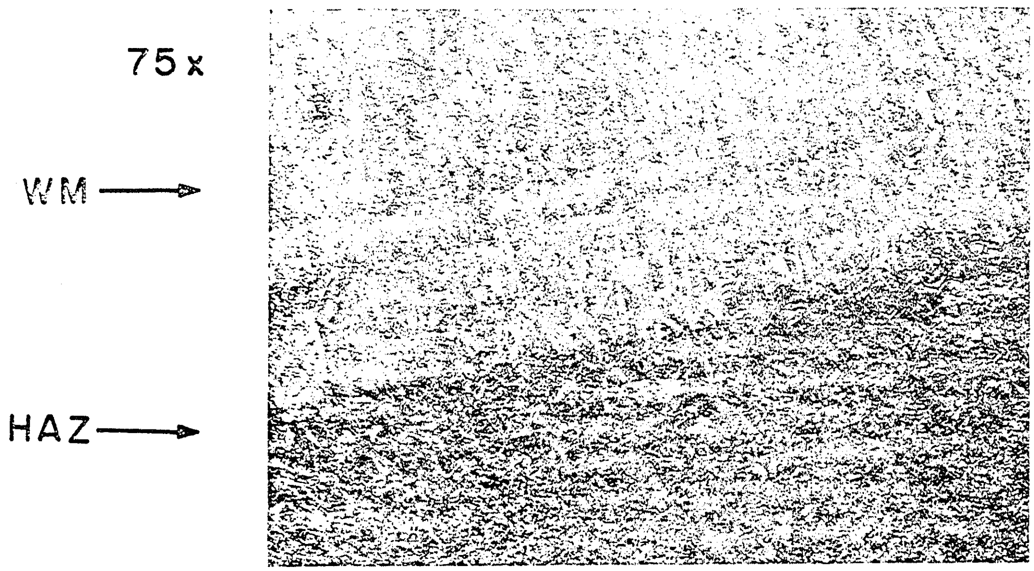


FIG. 23 MACROGRAPH AND MICROGRAPHS OF SPECIMEN GIC2

Macrograph 5x



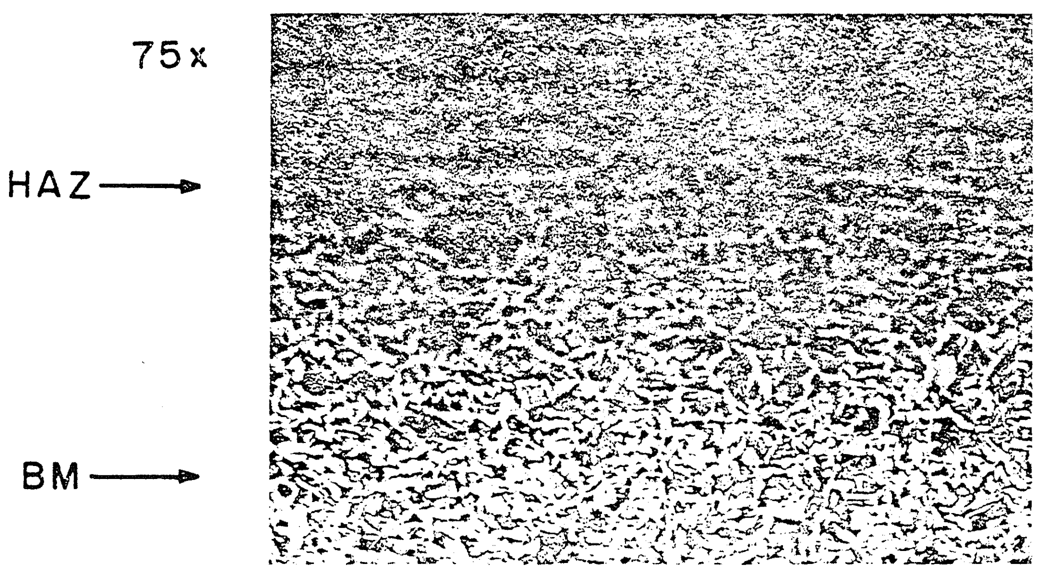


FIG. 24 MACROGRAPH AND MICROGRAPHS OF SPECIMEN GIC5

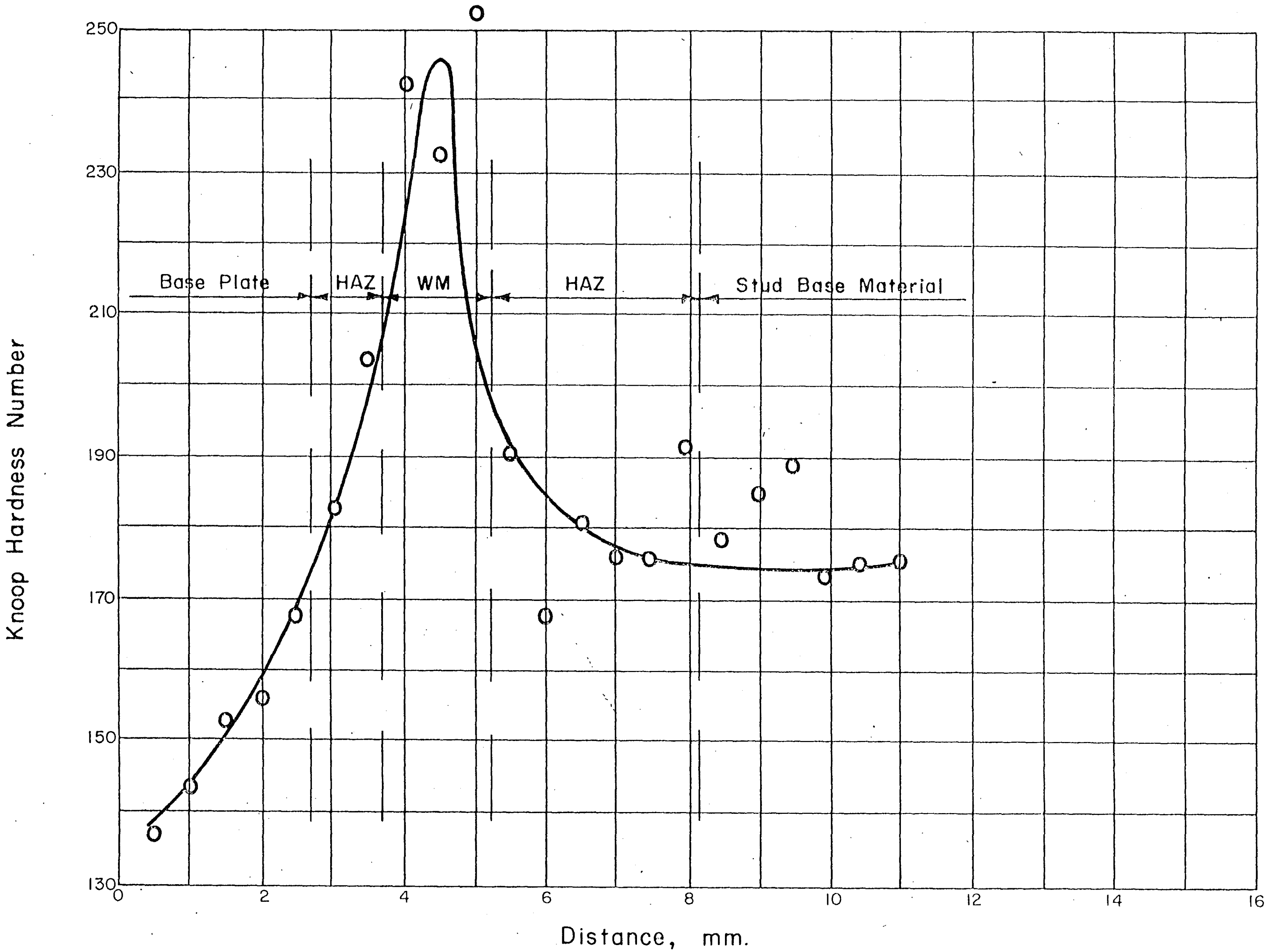


FIG. 25 HARDNESS SURVEY, SPECIMEN GIA 2

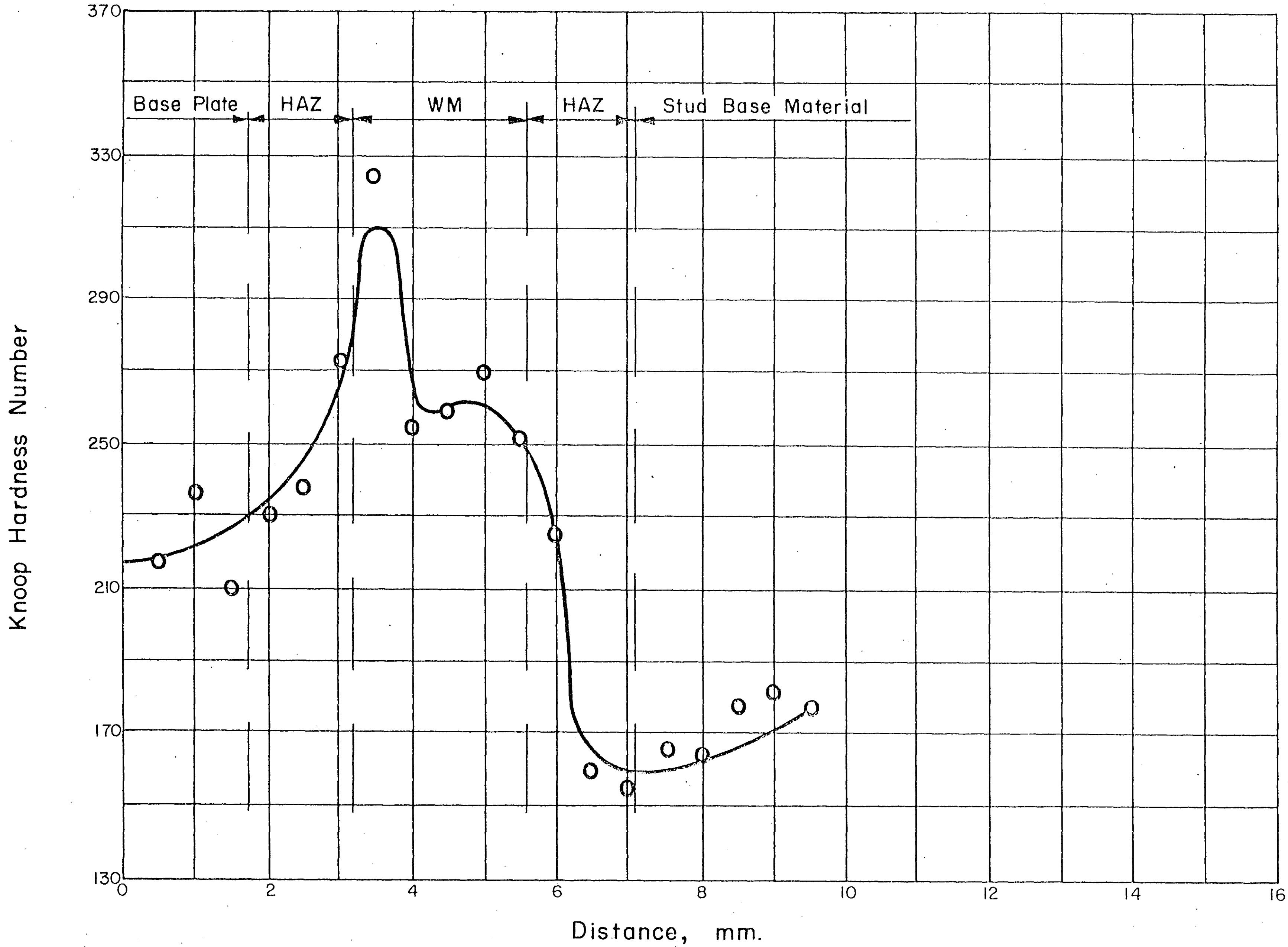


FIG. 26 HARDNESS SURVEY, SPECIMEN GIB I

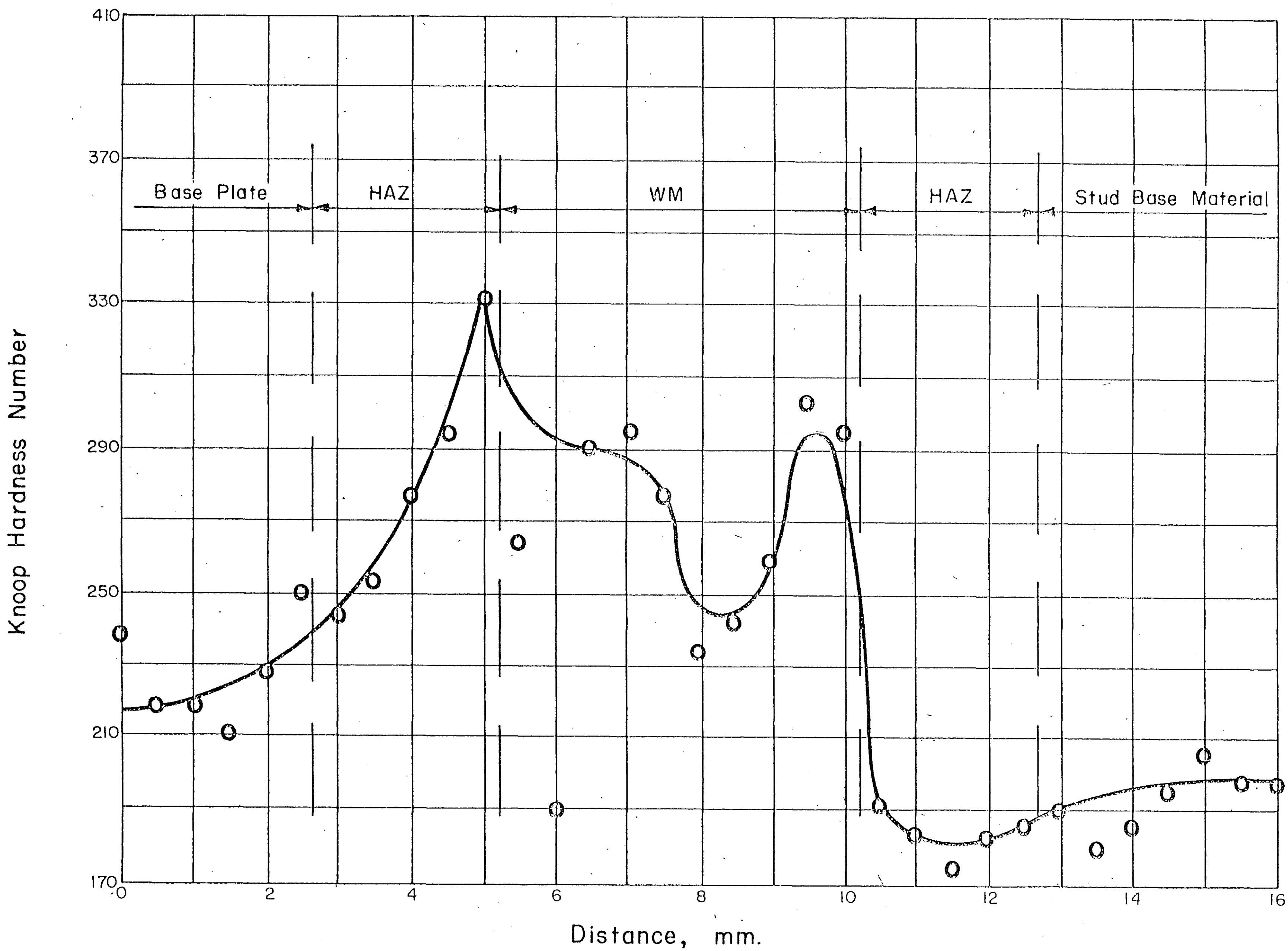


FIG. 27 HARDNESS SURVEY, SPECIMEN GIB 16

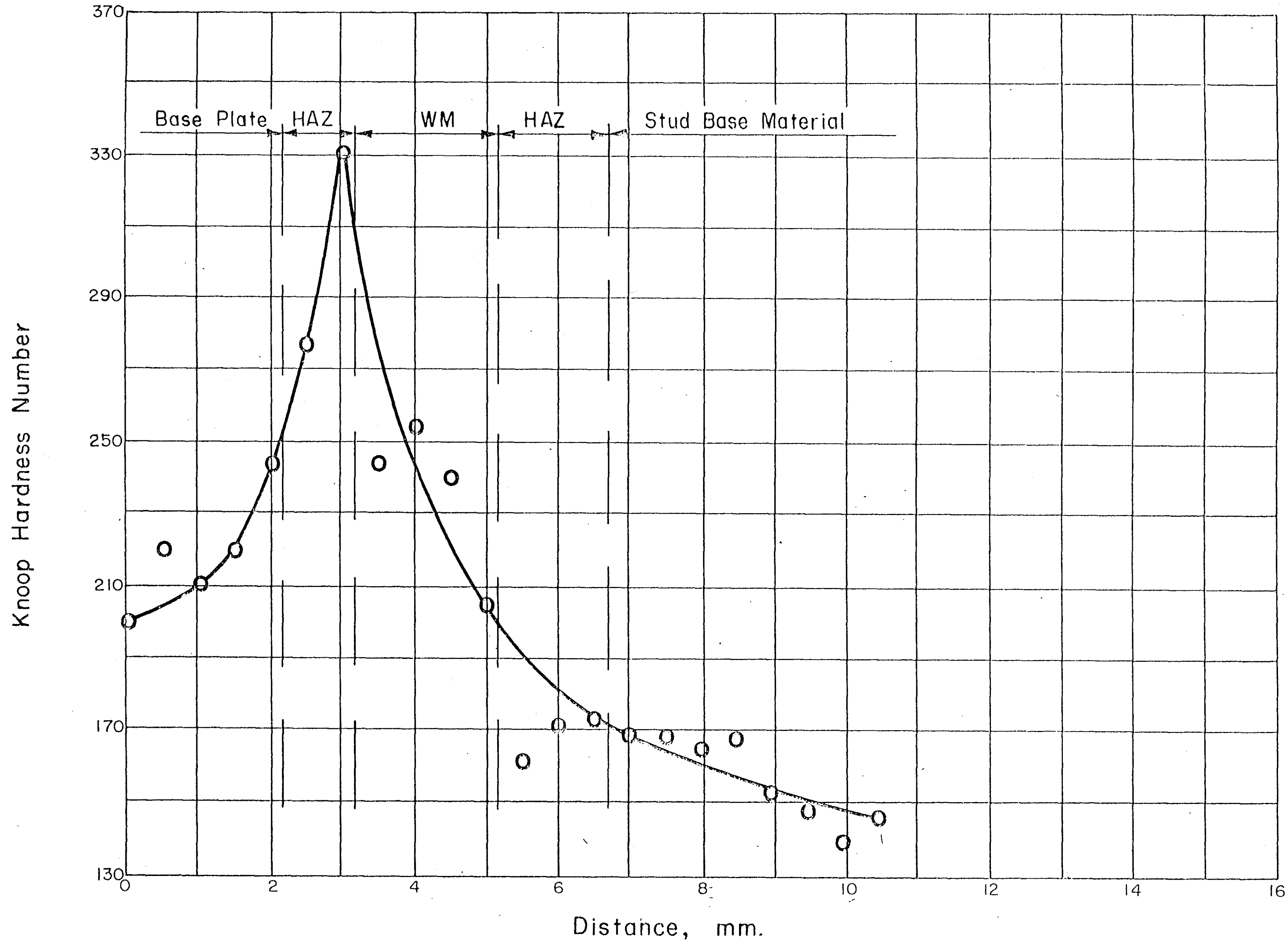


FIG. 28 HARDNESS SURVEY, SPECIMEN GIC 5

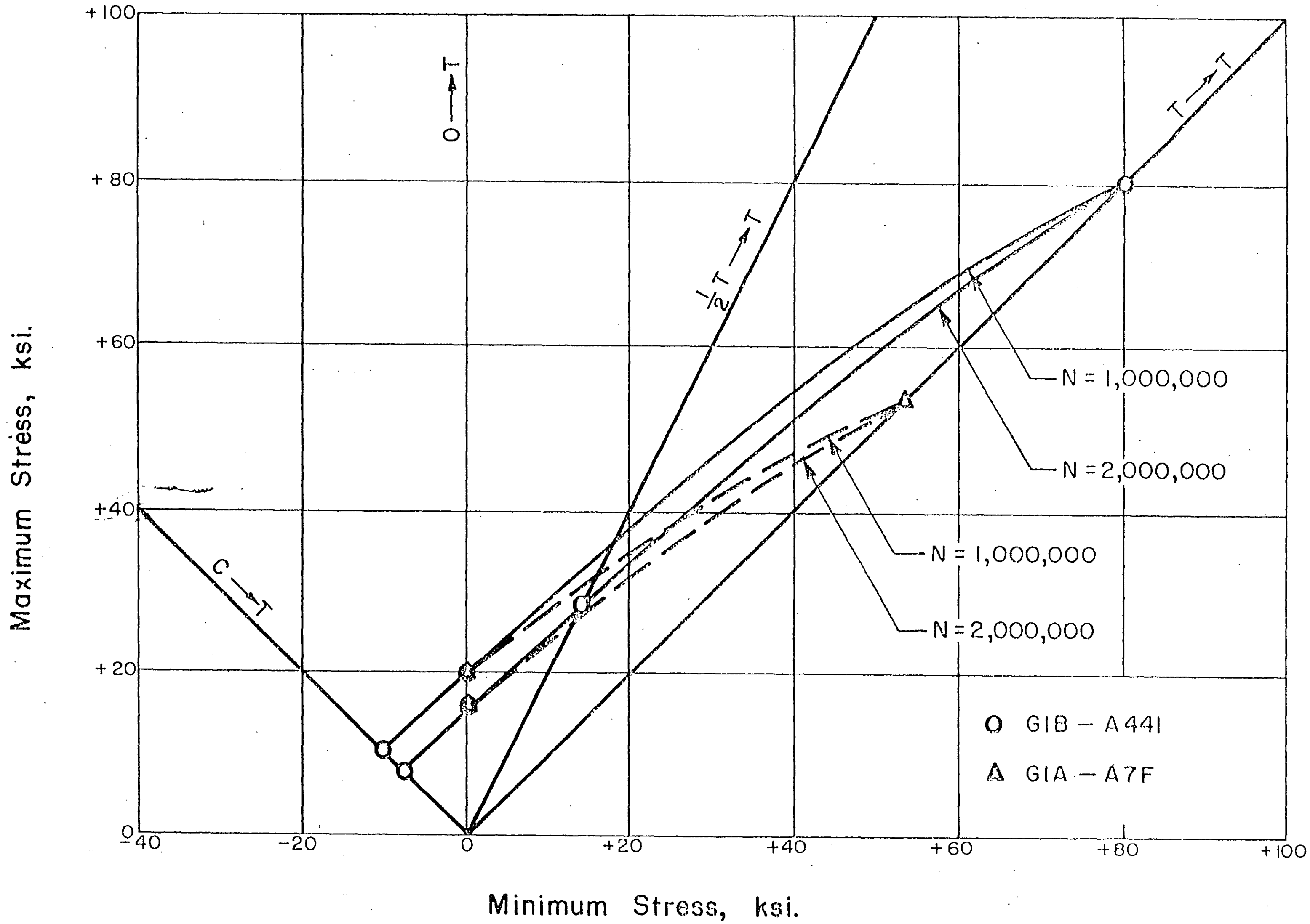


FIG. 29 MODIFIED GOODMAN DIAGRAM FOR GIA AND GIB SPECIMENS